Charles H. Eldridge
1929
Detroit, Mich.

ELEMENTARY
MAGNETISM AND ELECTRICITY

UNIVERSITY OF WISCONSIN
EXTENSION TEXTS

A series of Industrial and Engineering Education Textbooks, developed under the direction of Dean Louis E. Reber, University of Wisconsin Extension Division

Norris and Smith's
SHOP ARITHMETIC

Norris and Craigo's
ADVANCED SHOP MATHEMATICS

Hills'
MACHINE DRAWING

George's
ADVANCED SHOP DRAWING

Wooley and Meredith's
SHOP SKETCHING

Longfield's
SHEET METAL DRAFTING

Hobbs, Elliott and Consoliver's
GASOLINE AUTOMOBILE

Norris, Winning and Weaver's
GAS ENGINE IGNITION

Consoliver and Mitchell's
AUTOMOTIVE IGNITION SYSTEMS

Shealy's
HEAT

Shealy's
STEAM BOILERS

Shealy's
STEAM ENGINES

Jansky's
THEORY AND OPERATION OF D. C. MACHINERY

Jansky's
ELECTRIC METERS

Jansky's
ELEMENTARY MAGNETISM AND ELECTRICITY

Jansky's
PRINCIPLES OF RADIOTELEGRAPHY

Jansky and Faber's
PRINCIPLES OF THE TELEPHONE
Part I.—Subscribers' Apparatus

Hool's
ELEMENTS OF STRUCTURES

Hool's
REINFORCED CONCRETE CONSTRUCTION
Vol. I.—Fundamental Principles
Vol. II.—Retaining Walls and Buildings
Vol. III.—Bridges and Culverts

Blair's
SHOW-CARD WRITING

Pulver's
MATERIALS OF CONSTRUCTION

Frontispiece.

Apparatus used by students when studying this text.

INDUSTRIAL EDUCATION SERIES

ELEMENTARY MAGNETISM AND ELECTRICITY

PREPARED IN THE
EXTENSION DIVISION OF
THE UNIVERSITY OF WISCONSIN

BY

CYRIL M. JANSKY, B. S., B. A.
ASSOCIATE PROFESSOR OF ELECTRICAL ENGINEERING
THE UNIVERSITY OF WISCONSIN

FIRST EDITION
FIFTH IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1914

PRINTED IN THE UNITED STATES OF AMERICA

THE MAPLE PRESS - YORK PA

PREFACE

In the preparation of this text, the author has had in mind the needs of students who may have had some practical experience with electrical apparatus or machinery, but whose knowledge of the principles of its operation and of mathematics is limited. To make magnetic and electric principles real to such students, the subject is developed experimentally. The student is expected to perform simple experiments and thus to observe the actual phenomena. Then by questions and discussions he is aided in the interpretation of his observations, and the formulation of his conclusions into workable ideas.

In order that the subject may interest men in the electrical industries who are not technically trained, some practical applications of the fundamental magnetic and electric principles are illustrated and described. It is the writer's experience that such a presentation appeals strongly to the industrial worker who wishes to understand the *how* and *why* of things electrical.

The text is intended for individual or home study, although it may be used in class work when a supply of apparatus is available. This apparatus is inexpensive and most of it can be made by an ingenious student. It need not be exactly like that described in the text. The conversational style in which the work is written has been found very helpful in correspondence instruction as it seems to establish a personal relation between the student and instructor.

Although the text has been prepared for use in correspondence instruction, it is hoped that it may be of service to continuation schools, Y. M. C. A. schools, and plant schools that give a course of like nature.

The author is under obligation to Mr. G. G. Thompson, engineer of the Cutler Hammer Company, for reading the manuscript and for making many valuable suggestions, and to Mr. G. R. Wells for making the line drawings. The author also wishes to express his appreciation of the kindness of the various manufacturers of electrical apparatus and machinery who have furnished illustrative material.

C. M. J.

The University of Wisconsin,
Madison, Wisconsin,
January, 1914.

CONTENTS

LIST OF EXPERIMENTS

ELEMENTARY MAGNETISM
AND
ELECTRICITY

CHAPTER I

MAGNETISM

1. Introduction.—The subject of magnetism and electricity is best approached from the experimental side, for only by such means will the interactions of magnetic and electric forces become real to the student. The handling of the apparatus, together with reports upon the observed phenomena, is about the only way in which a student can get a clear understanding, or realizing sense, of electric and magnetic principles. Thus the generation of an electromotive force in a dynamo is merely due to relative motion between a magnetic field and copper wire, and, unless the student has a clear notion of a magnetic field and the interaction between conductor and field, he can never get a clear understanding of the fundamental principle of all dynamo-electric machinery. We shall thus begin this course with a study of magnetism and learn why magnets are important industrially.

2. Magnetism.—The essential nature of the property called magnetism is unknown. We only know that under certain conditions a piece of iron, or steel, acquires the property of attracting other pieces of iron by a force which is many times as great as the force of attraction between the two pieces due to gravity, and also that there is a reaction between this property and a like property of the earth which tends to cause the piece of iron to assume a definite position with reference to the earth's meridian, that is, a north and south line.

By magnetism is thus meant the property a body has of attracting iron with a force which is neither gravitation nor due to mechanical action of ordinary matter, and which will tend to set the body in a north and south direction.

This definition clearly does not tell us much about magnetism, it merely enables us to distinguish between magnetic forces and other forces. We thus recognize a magnet by its action. The fact that some substances possess this property has been known for centuries. An iron ore which was first found in Magnesia (Asia Minor) was first observed to possess this property and from this the word magnet was undoubtedly derived. This iron ore, commonly called lodestone, which means attracting stone, has no industrial use based on its attracting property.

3. Magnets.—A body possessing the property of magnetism is called a magnet. The only substance of which commercial magnets are made is iron or some of its forms, although there are other substances that can be magnetized. To this class belong nickel, cobalt, manganese, and an interesting alloy named after its inventor "Heusler's alloy." This is an alloy of copper, manganese, and aluminum. Recently several other such alloys,

Fig. 1.

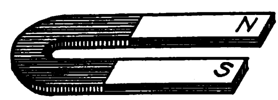

Fig. 2.

all containing either manganese or chromium, have been found to possess magnetic properties.

4. Permanent and Temporary Magnets.—Before the discovery of the relation between magnetism and an electric current, magnets were made by stroking the lodestone with a piece of iron. When the lodestone was touched with a piece of iron the iron itself acquired the property of attracting other pieces of iron, or as we now say became magnetized. The time during which this property of attraction was retained depended upon the quality of the iron. If, upon removal from contact with the lodestone, the iron lost most of its magnetism, it was called a *temporary magnet.* A piece of steel which was hardened before magnetizing retained its magnetic properties indefinitely and accordingly was called a *permanent magnet.*

Magnets are now made either by stroking a permanent magnet in one direction by the piece of steel to be magnetized, or by passing electric currents about the steel bar in a manner to be described later.

5. Forms of Magnets.—Forms of commercial magnets are too numerous to mention. The two common forms of permanent magnets are the bar, Fig. 1, and horseshoe, Fig. 2.

6. Experiment 1. Poles of a Magnet.

Apparatus.—

Bar magnet
Iron filings

Operation.—Take a shallow pasteboard box, like a thread box, and spread the iron filings over the bottom of it. Take one of the bar magnets and lay it flat upon the iron filings; turn the magnet over and lift it from the box. Do the iron filings adhere, or stick, to all parts of the magnet? Draw a diagram showing the parts to which the iron filings adhere. The parts near the ends of a magnet to which iron filings cling are called the poles of the magnet. Take a magnetic needle and dip it into the iron filings in the same way. Does it too have poles? Remove the iron filings by brushing with a cloth Never strike the magnet to dislodge the iron filings.

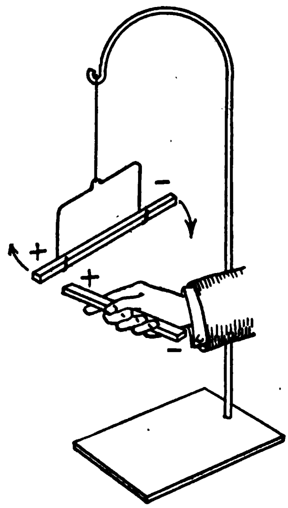

Fig. 3.

7. Experiment 2. Laws of Magnetic Attraction.

Apparatus.—

Two bar magnets
Supporting stirrup

Operation.—Arrange a stirrup of wire supported by an untwisted thread as indicated in Fig. 3. Place one of the bar magnets in the stirrup and note which end points north. Mark this end + with a pencil or a piece of chalk. Replace the bar magnet by the second magnet and also note which end points north. Now take bar magnet No. 1, and hold the + end near the + end of the bar magnet in the stirrup. Observe carefully whether there is an attraction or repulsion between the magnets. Repeat this several times until you are certain of the result. Reverse the bar magnet held in the hand and repeat the experiment. Perform the same experiment with the other end of the suspended magnet. Formulate your answers like this:

Like poles $\left\{\begin{matrix}\text{attract}\\ \text{repel}\end{matrix}\right\}$ each other.

Unlike poles $\left\{\begin{matrix}\text{attract}\\ \text{repel}\end{matrix}\right\}$ each other.

Use the correct word attract or repel in each case.

8. Experiment 3. Variation of Attraction with Distance.

Apparatus.—

Compass needle
Bar magnet

Operation.—It will be impossible to get exact values with the simple apparatus at hand, but an idea of the variation of the force of attraction and repulsion may be obtained if this experiment is carefully performed. Place the mounted compass needle and bar magnet in the relative positions shown in Fig. 4. First note and record the reading or position of the compass needle before the magnet is brought near. After placing the magnet in position, measure the distance *d* and read the deflection of the compass needle. That is, through what angle has the needle been deflected? If the original position of the *N*-end was on 0 degrees and after the magnet is brought near it is 20 degrees, the deflection is 20 degrees. If, however, the original position is 10 degrees and second position 20 degrees the deflection is only 20 degrees − 10 degrees = 10 degrees. Repeat this by moving the bar magnet farther and farther from the compass. Make observations for at least 5 positions of the bar magnet. Tabulate your results as follows:

Setting	*N*-Pole near *N*-Pole	
	d	Deflection
1		
2		
3		
4		
5		

9. Theory.—The results of this experiment will not give the exact variation or relation between deflection and distance between magnet poles. In the first place, both poles of the bar magnet influence both ends of the compass needle, and then again the relation between *d* and deflection is not constant. The important point for the beginner in the experiment is the fact that the deflection decreases as the distance *d* increases. Many

refined experiments have been performed which show that the force of attraction or repulsion between the two poles decreases as the square of the distance between them. If we express this relation algebraically, that is in symbols, we get

$$\text{Force} = \frac{\text{strength of one pole} \times \text{strength of other pole}}{\text{square of distance between them}}$$

$$\text{or } F = \frac{m_1 \times m_2}{d^2}$$

where m_1 and m_2 are pole strengths expressed in the same units and d is the distance between the poles.

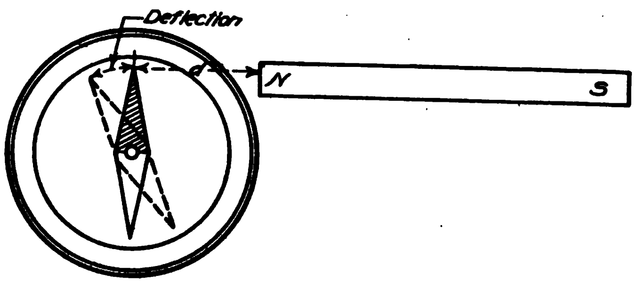

Fig. 4.

10. Unit Pole.—In the foregoing expression, the letter F stands for "force," but in what units this force is measured will depend upon the assumed unit of pole strength. The results of experiment 1 show that the iron filings adhered to the ends of the bar magnet. These ends are usually called poles, but as the surface to which the iron filings cling is quite extended, they may be called distributed poles. The definition of unit pole is based on the assumption that all of the magnetic influence is concentrated upon one point. Under this restriction the unit pole is a point pole which repels with a force of one dyne an equal point pole placed 1 cm. away in air. A dyne is a unit of force and is approximately about 1/980 of a gram, or 1/445000 of a pound. The force exerted by two unit poles is thus very small. The force of repulsion or attraction between two magnet poles is then a measure of the magnetism in the poles. Thus, if one of the poles is a unit pole, and, when another pole is brought near, the force is 200 dynes, we say that the unknown pole contains 200 units of

magnetism or has 200 unit-poles strength. The centimeter is a unit of length and equals 0.3937 in.

EXAMPLE

Two poles of 10 and 15 units strength respectively are placed at a distance of 15 cm. apart. What is the force between them?

Solution.—

$$F = \frac{m_1 m_2}{d^2}$$

$$m_1 = 10 \text{ units}$$

$$m_2 = 15 \text{ units}$$

$$d = 15,\ d^2 = 225$$

Hence, $F = \dfrac{10 \times 15}{225} = 2/3$ dynes.

11. Properties of Space Surrounding a Magnet.—It is important to know whether these unique properties of a magnetized bar are confined to the surface of the bar, or whether they extend out into space, and if the influence does extend into space, what are some of its characteristics. This problem can also be best investigated by experiment.

12. Experiment 4. Magnetic Field.

Apparatus.—

Bar magnet
Horseshoe magnet
Iron filings
Several sheets of paper

Operation.—Place one of the bar magnets on a horizontal surface and upon the magnet place a sheet of stiff writing paper or a piece of cardboard. Arrange the paper so that it is horizontal and smooth. Put some iron filings into a cheesecloth bag and sift them upon the paper, tapping the paper gently while the iron filings are being sifted. Note carefully the manner in which the iron filings arrange themselves. Pour the iron filings back into the cheesecloth bag and repeat to see if the same, or nearly the same, configuration of iron filings can be reproduced. If so, take another sheet of paper and on it draw an outline of the bar magnet. On this same sheet draw pencil lines representing the arrangement of the iron filings.

Another method of obtaining the distribution of the iron filings is to place upon the bar magnet a pasteboard, and upon the pasteboard spread smoothly a piece of blue-print paper, sensitized side up. Sprinkle iron filings upon the blue-print paper as before,

and when a proper pattern has been obtained, expose the blue-print paper and iron filings to the sun for two or three minutes. Shake off the iron filings in a dish and wash the blue-print paper in a basin of water. If the experiment is carefully performed there will be left on the blue-print paper a tracing of the iron filings.

13. Theory.—This experiment shows that the magnetic influence permeates the space about the iron bar. The space around a magnet which is permeated by a magnetic influence is a magnetic field. When a magnetic substance, such as the iron filings, is placed within the field, it becomes magnetized and sets itself in a definite line. The iron filings become small magnets, and as already pointed out, when two magnets are brought near each other a force is exerted between them. This force causes the iron filings to make certain designs as shown in Fig. 5. This representation of a magnetic field is only in one plane, that is, in the plane of the paper which was laid on the bar magnet. A similar design will be obtained if the magnet is turned on edge or in any position parallel to its length. This means that the magnetic field completely surrounds the bar magnet and is carried with it when the magnet is moved.

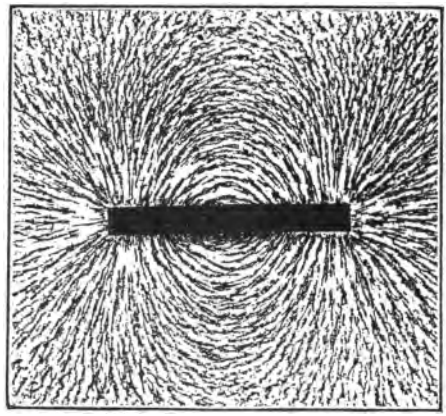

FIG. 5.

14. Unit Magnetic Field.—Just as the strength of a magnetic pole is measured by the force it exerts on a unit magnetic pole, the strength of a magnetic field is defined in terms of the force it will exert upon a unit magnet pole. If a small compass be placed on the paper above the bar magnet, the magnetic needle will lie parallel or be tangent to the lines as shown in Fig. 6. The north pole of the compass needle is pulled in one direction and the south pole in the opposite direction. The magnetic field thus exerts a force upon the magnetic needle. If it were possible to isolate a north pole and place it on the plane of the paper it would, if free,

move from the north pole of the bar magnet toward the south pole. This force that a magnetic field is capable of exerting upon a magnet pole is used to define the field strength, a unit field being defined as follows:

A magnetic field of unit strength is one which is capable of exerting a force of one dyne upon a unit magnet pole. The unit of magnetic field strength or intensity is called the *gauss* after the famous German physicist and mathematician.

15. Representation of a Magnetic Field.—Since the iron filings are arranged in lines or rows, it is customary in practice to speak of the magnetic field as consisting or being composed of lines, and the strength of field is then represented by the number

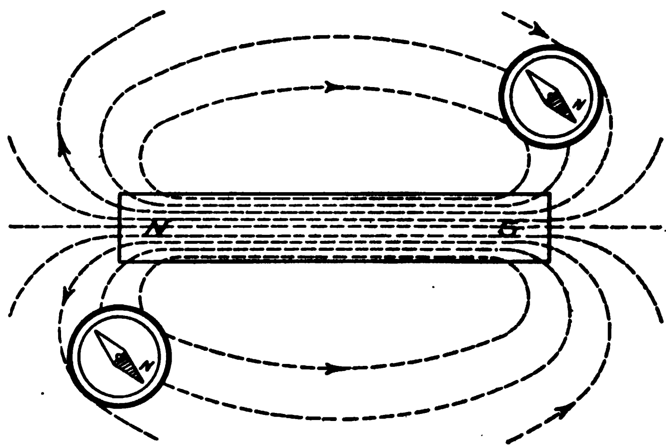

FIG. 6.

of lines per square centimeter or per square inch, in a plane at right angles to the magnetic field. A field of unit strength is then represented by one line per square centimeter, and a field of ten units by ten lines, etc. The student must remember, however, that this is merely a method of representing a magnetic field. The magnetic field occupies or permeates all of the space near and around a bar magnet. Usually the field is not of uniform strength at every point, but there is no point in the space around the magnet entirely free from a magnetic field. The ether surrounding a bar magnet is not fibrous like a muscle; the system of lines is used merely for convenience in making calculations, and the development of the electro-magnetic theory.

16. Experiment 5. Magnetic Field around two Magnets.

Apparatus.—

Two bar magnets
Iron filings
Paper

Operation.—This experiment is performed exactly in the same manner as experiment 4. The two bar magnets are placed on a horizontal surface, parallel to each other, and about 1 in. apart. First place unlike poles near each other and sprinkle iron filings upon the paper as before. Draw a diagram showing the arrangement of the iron filings. Do the bar magnets attract or repel each other?

Next reverse one of the bar magnets and repeat. Again draw a diagram showing the distribution and arrangement of lines. Compare this with the previous diagram. What differences are observed? In which case is there an attraction? In which case is there a repulsion between the magnets?

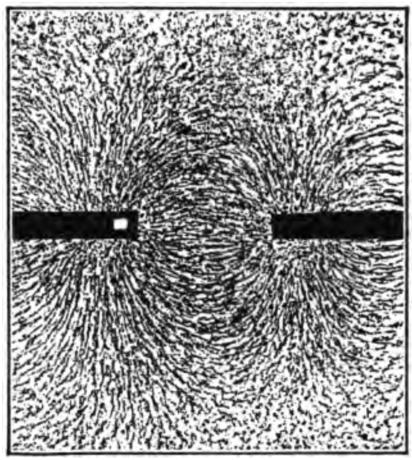

Fig. 7.

17. Theory.—An examination of the diagrams obtained from experiment 5 will show that when the unlike poles are near each other the iron filings are arranged in lines extending from one pole of one magnet to the near pole of the other magnet. We say that the magnetic lines pass from one magnet pole to the adjacent pole of the other magnet.

The other diagram shows that when like poles are near, the lines from one magnet do not enter the other magnet, but are pushed aside. In the first case the tension along the lines tends to draw the bar magnets near each other while in this case there is manifest a force of repulsion. Although this does not fully explain why, it shows that unlike poles attract and like poles repel. Figs. 7 and 8 show the characters of the magnetic fields between unlike and like poles when the bar magnets are placed end to end.

18. Magnetism a Molecular Property.—Although the exact relation between the property called magnetism and the physical structure of a magnetic substance is not known in detail, a theory which helps in the understanding of certain well-known phenomena has received almost universal acceptance. The elements of this theory will be brought out by the following experiment.

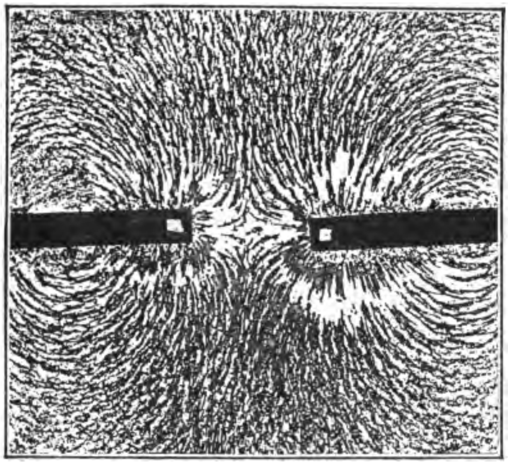

FIG. 8.

19. Experiment 6. Molecular Theory of Magnetism.

Apparatus.—

Compass
Bar magnet
Sewing needle
Iron filings
Small round bottle or test tube

Operation.—Fill the small bottle with iron filings and test for polarity. That is, first, hold one end of the bottle near the north pole of, and at right angles to, the magnetic needle. Turn the bottle end for end, and again test. Does the bottle act as a bar magnet or as an unmagnetized piece of iron?

Next stroke the bottle with one end of a bar magnet from end to end as indicated in Fig. 9. Without shaking or jarring the iron filings, again test for polarity. Have magnetic poles been developed? Shake the bottle so as to disarrange the iron filings

and again test for polarity. Repeat this process until you are certain of your results.

Take a large, unmagnetized sewing needle and dip it into iron filings; no filings will cling to it. Magnetize the needle by stroking it from one end to the other with one pole of the bar magnet; dip it into the filings again and observe that the filings adhere near the ends of the needle. Break the magnetized needle and dip the pieces into the filings. Do the filings adhere to the ends of the pieces? Are the pieces also magnets? Break one of the pieces in two and repeat. Are the small pieces magnets? Test each piece for polarity.

20. Theory.—The theory of the physical structure of bodies is to the effect that if it were possible to continue the subdivision indefinitely, we should obtain ultimately a particle which was incapable of further subdivision by mechanical means, such as grinding, dissolving, etc. If we use chemical means to further subdivide the particle the kind of matter is changed. Either the particle is decomposed into simple substances, or combined with other substances, but in either case it no longer has the same properties. This mechanically indivisible particle is a molecule and all bodies are supposed to consist of molecules.

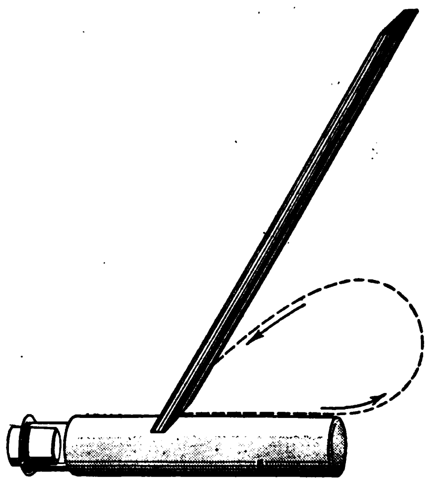

Fig. 9.

The experimental facts concerning the magnetic properties of small pieces of iron or steel point to the conclusion that the arrangement of the molecules has something to do with magnetism, for when the iron filings were in a jumbled mass no external magnetism was apparent. When the bottle was subjected to a magnetic influence the iron filings assumed definite positions and the whole mass developed poles. A sudden violent disturbance, however, weakened or destroyed this magnetism.

The process of breaking the smaller pieces of the needle in two can be continued indefinitely and after each division it will

be found that the pieces are magnets. A careful test by the student will show that this is well illustrated by Fig. 10.

To explain this phenomena it is assumed that the molecules are themselves small magnets, and that ordinarily they are arranged in closed magnetic circuits within the bar. When, however, the bar is subjected to a magnetizing force, the molecules are forced to arrange themselves in such a way that the N-poles point in one direction and the S-poles in the opposite direction.

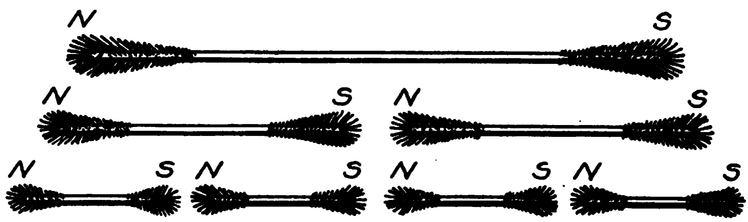

FIG. 10.

Under such an arrangement the opposite poles of the molecules neutralize each other in the bar of iron, but at the ends the poles are exposed and the magnetic influence extends into surrounding space. This theory is illustrated in Figs. 11, 12, and 13. The supposed arrangement of molecules of an unmagnetized bar is shown in Fig. 11. The molecules are represented by small rectangles, and opposite poles by light and shaded portions.

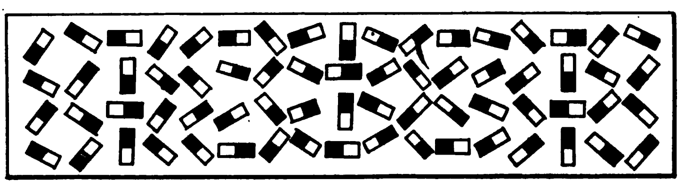

FIG. 11.

As is shown, the molecules are arranged in a haphazard way but forming closed magnetic circuits.

In Fig. 12 the molecules are shown in a more symmetrical arrangement, but not all pointing in the same direction. This would represent the condition in a bar magnetized, but not to its greatest possible value. In Fig. 13 all the molecules are shown as pointing in the same direction and under these conditions the bar is said to be a saturated magnet. The student must remem-

ber that there is no absolute proof that these conditions actually exist as here represented. The theory explains the phenomena better than any other so far proposed. Likewise, the reader must not suppose that molecules are rectangular in cross-section. What shapes molecules may have no one knows.

21. Magnetic Induction.—The change produced in the arrangement of the molecular magnets when in the presence of a magnet or under the influence of a magnetic field is called magnetic

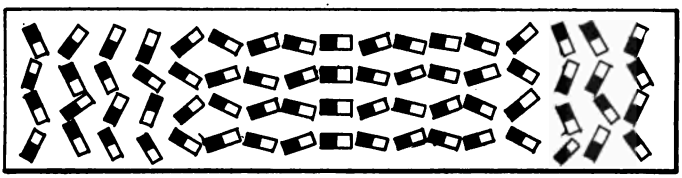

Fig. 12.

induction. The next experiment will show that only some substances can be magnetized by induction.

22. Experiment 7. Magnetic Induction.

Apparatus.—

Bar magnet
Nails
Piece of copper wire
Match
Iron filings

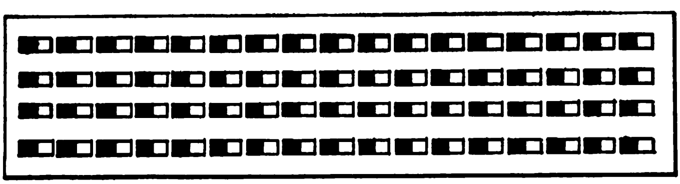

Fig. 13.

Operation.—Dip the point of a nail into iron filings and notice if any filings adhere, or cling to it, when it is withdrawn. Again dip the point of the nail into the filings, and while in this position hold one end of the bar magnet against the head of the nail. Do the iron filings adhere to the point of the nail while the magnet is touching the head? Remove the bar magnet and see if as many filings cling to the point. Why? Repeat this by using a

copper wire, a match, a glass rod in place of the nail. What do you learn?

23. Theory.—Touching the nail made a temporary magnet of it, or in other words, developed magnetic properties within it. The development of magnetism within a body when placed in the vicinity of a magnet is called magnetic induction. Magnetism is said to have been induced in the nail when it was touched with the bar magnet. When the bar magnet was removed from contact with the nail, most of the magnetism disappeared; the small amount that remained is called residual magnetism. This residual magnetism is usually sufficient to supply the initial excitation in electrical generators.

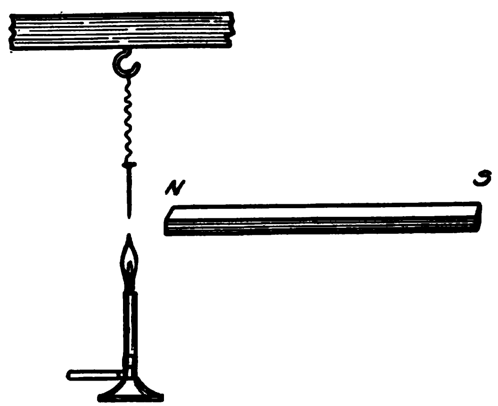

FIG. 14.

The experiment also shows that magnetism can be induced in iron, but not in copper, wood or glass. Substances in which magnetism can be induced are called magnetic, or para-magnetic. Those in which magnetism cannot be induced are called non-magnetic. There is still another class of bodies which when brought near a bar magnet are repelled. Bismuth is the best example of this class.

24. Experiment 8. Effect of Heat on Magnetism.

Apparatus.—

A gas burner or lamp (an alcohol lamp is best)
Nail
Bar magnet

Operation.—Suspend a small nail by means of a thin wire, as

shown in Fig. 14. Heat the nail to red heat and bring the bar magnet near it. Does the bar magnet attract the nail? Remove the lamp, and after the nail has cooled again test it for magnetism. Does the nail regain its magnetic properties?

Magnetize a sewing needle and then heat it to redness, and dip the needle after heating into iron filings. Is the needle still a magnet?

25. Theory.—According to the molecular theory of magnetism, the development of magnetism is explained on the assumption that the particles of iron are turned under the influence of the magnetizing field. The iron itself becomes for the time being a magnet, or magnetism is induced in the iron. At red heat, iron loses its magnetic quality. This means not only that a magnet may be demagnetized by being heated to about 800 degrees Centigrade, but also that iron, when heated to this temperature, is no longer capable of being attracted by a magnet. On cooling, however, the iron regains its magnetic quality at a somewhat lower temperature.

According to the kinetic theory of matter all molecules are supposed to be in motion. This motion is greatly increased by heat; hence, heating a magnet will cause the molecules to move so rapidly that they cannot be kept "lined up" by the influence of the magnetic field.

26. Magnetism of the Earth.—The fact that there is a magnetic field around the earth is well shown by the behavior of a magnetic needle. The presence and influence of this field is not always realized. The following experiment will aid greatly in understanding this influence.

27, Experiment 9. Terrestrial Magnetism.

Apparatus.—

Mounted magnetic needle
About 2 ft. of 3/4-in. or 1-in. gas pipe
Hammer

Operation.—First test the piece of gas pipe for magnetism by holding one end of the gas pipe near the N-pole of a magnetic needle and observe whether the magnetic needle is attracted or repelled. Reverse the pipe and test the other end. If both ends of the gas pipe attract the magnetic needle, the gas pipe is not magnetized and the rest of the experiment may be performed.

Hold the gas pipe in the left hand in a north and south position, the north end dipping downward. While in this position hit the

pipe several hard blows with the hammer and again test the pipe for magnetism as before. Is the pipe a magnet, that is, does one end of the pipe attract and the other end repel the needle? Can you explain this?

Turn the gas pipe end for end and again hold it in a north and south position as before and hit it several more blows with the hammer. Test for magnetism as before and notice if the end of the pipe that formerly attracted the N-end of the needle still attracts it. Make all your tests with the N-pole of the magnetic needle. If you find the magnetism of the gas pipe has been reversed, explain.

28. Theory.—That the compass needle pointed in an approximately north and south direction was known in the time of Columbus. It was, however, in 1860 that Dr. William Gilbert, physician to Queen Elizabeth, first explained the behavior of the compass needle by the assumption that the earth itself is a magnet with a south pole near the geographical north pole, and a north pole near the geographical south pole. The correctness of this assumption has since been completely verified. The earth is thus surrounded by a magnetic field in exactly the same manner as the bar magnet that has been used in the preceding experiments. This field is quite weak but it controls the magnetic needle when it is free to swing. Furthermore, it was shown that when a nail or other non-magnetized body is subjected to the influence of a bar magnet, it (the nail) becomes magnetized. In exactly the same way, when an un-magnetized body is subjected to the earth's magnetic field it, too, will become magnetized. On account of its weakness, the earth's field will not magnetize a body so readily or to the same degree as the bar magnet. In the preceding experiment, when the piece of pipe is held in a north and south position with the north end dipping below the horizon, it is approximately in the same direction as the earth's magnetic field. The magnetic field of the earth attempts to "line up" the molecules but without help it is too weak to have any permanent effect. When the gas pipe is suddenly jarred, as when it is hit with the hammer, the force exerted by the earth's field is sufficiently strong to align enough of the molecules so that the pipe behaves as a magnet. It is thus magnetized by the action of the earth's magnetic field. When the pipe is reversed the influence of the earth's field is exerted in the opposite direction and its magnetism is reversed.

Any one working in a machine shop has undoubtedly observed that tools become magnetized. A good example is the vertical drill to which the chips cling when it is withdrawn from the hole being drilled.

29. Declination.—The earliest users of the compass were aware that it did not point exactly north and south, but it was Columbus who, on his first voyage, discovered that the compass needle did not point in the same direction at all points on the earth's surface. The chief reason for this deviation from a true north and south direction is the fact that the earth's magnetic poles do not coincide with the geographic poles. There are, however, other causes, such as large deposits of iron ore, etc. The angle which the needle

Fig. 15.

makes with the meridian at any place is called the *declination* at that place. In making land surveys with a compass the declination must be taken into account.

30. Dip.—If an unmagnetized bar be suspended so that it is in a horizontal position and then magnetized it will be found that it no longer remains horizontal. In the northern hemisphere the north seeking end will dip below the horizon. This shows that the earth's field is not horizontal but dips toward the north. This is the reason why the gas pipe should be held with the north end lower than the south end when it is struck with the hammer. The angle between the horizontal and the direction of magnetic lines is called the angle of dip. In the latitude of Madison this angle is about 73°.

31. Practical Uses of Permanent Magnets.—The earliest use of the permanent magnet was to determine direction, that is, as a compass needle. It is still very extensively used for this purpose, both on land and sea. For land use, the needle usually is in the form of a slim bar magnet pivoted on a jewel bearing at the middle. One form of surveyor's compass is shown in Fig. 15.

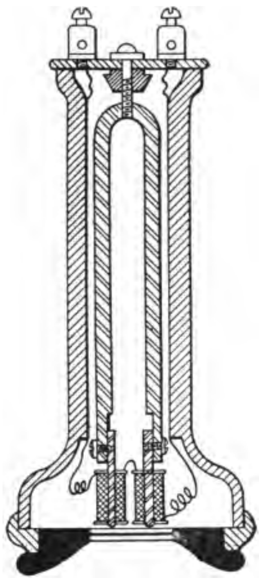

FIG. 16.

A mariner's compass is made in a somewhat different form. The points of the compass and the circle divisions are printed on a paper ring which is attached to a light aluminum rim. Radial threads connect the ring to a central disk which contains a sapphire cap by which the dial is supported on an iridium point. Eight small magnets of glass-hard steel are tied to the radial thread, four on each side of the jewel cap. The directive force is thus due to the action of the earth's magnetic field upon the small magnets.

Another important use of the permanent magnet is in the telephone receiver. This also has several forms, one of which is shown in Fig. 16. As shown in the figure the yoke consists of a

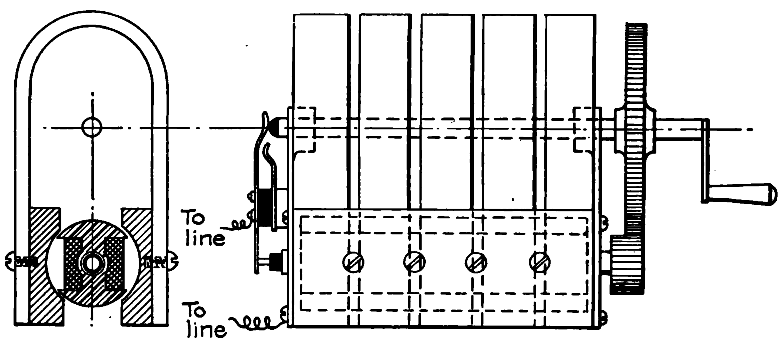

FIG. 17.

piece of soft iron bent into the horseshoe form. To the end of this are attached steel pole pieces. Surrounding the pole pieces

are two coils of fine wire. Permanent magnets are used in telephone receivers for two reasons: In the first place, they give a more positive and stronger action to the diaphragm, and in the second place, if they were not used the sound at the receiver

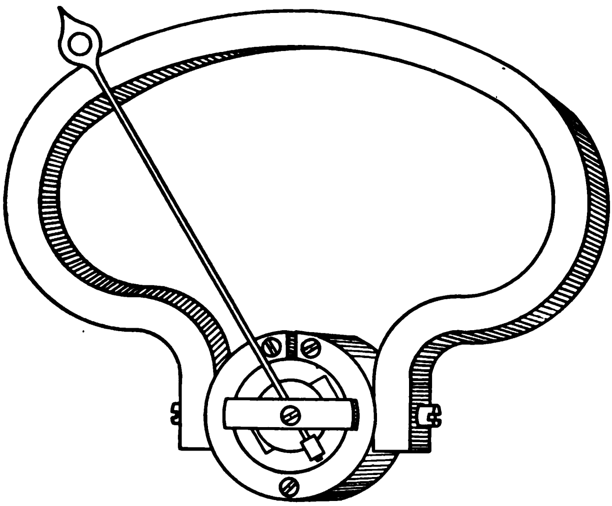

Fig. 18.

would be an octave higher than that at the transmitter causing it. Unscrew the cap from the telephone receiver supplied with the apparatus and examine its construction. Replace the diaphragm by a sheet of paper and sprinkle iron filings over it so as to determine the magnetic field.

Fig. 19.

Permanent magnets of the horseshoe form are also used on the magneto ringer as well as magneto generator used on automobiles for ignition. The telephone magneto ringer is shown in Fig. 17.

The operation of nearly all forms of direct-current measuring

instruments depends upon the interaction between the magnetic field of a permanent magnet, and the magnetic field due to a current. Likewise the retardation of energy meters is nearly always due to the action of horseshoe magnets of the permanent type. The form of magnet employed in measuring instruments is shown in Fig. 18, and the drag magnets of a watthour meter are shown in Fig. 19. Magnets intended for use in measuring instruments must not change in strength appreciably with time. They must not only be magnetized to a high degree, but must also retain their magnetism indefinitely

Another interesting use of magnets is for the removal of iron filings from the eye or other places where they may have accidentally lodged. A more extended discussion of the uses of magnets will be given after electromagnetism is studied.

RECAPITULATION

1. *Magnetism* is the name of an assumed substance producing attraction or repulsion between pieces of iron by action at a distance.
2. *Magnets* are bodies possessing the property of *magnetism.* Commercial magnets are made exclusively of iron. *Permanent magnets* are made of hardened steel and retain their magnetism indefinitely. *Temporary magnets* are made of soft iron or soft steel and retain their magnetism only so long as they are subjected to a magnetic influence.
3. *The poles* of a magnet arc thc ends or points at which the magnetism is concentrated.
4. *The laws of magnetic attraction* are: (a) *Like poles repel* and *unlike poles attract.* (b) The forces of attraction or repulsion are proportional directly to the product of the pole strengths and inversely as the square of the distance between them.
5. *The strength of a magnetic pole* is the quantity of magnetism at the poles. It is measured by the force the magnet pole exerts upon a unit pole.
6. *Unit pole strength* or a *unit pole* is that pole strength which repels a like pole of equal strength at a distance of 1 cm. in air, with a force of one dyne. A dyne is approximately equal to 1/445000 lb. avoirdupois.
7. *A magnetic field* is the region or space which is permeated by a magnetic influence.
8. *A unit magnetic field* is one which is capable of exerting a force of one dyne upon a unit magnet pole.
9. *The strength of a magnetic* field is usually represented graphically

by the number of lines per square centimeter in a plane at right angles to the field.

10. According to the *molecular theory of magnetism,* every molecule of a piece of a magnetic substance is a magnet. When the magnetic body is neutral, that is, has no magnetic field of its own, the molecules are assumed to be arranged either haphazard or in little closed groups or chains, so that, on the whole, opposite poles neutralize each other throughout the bar. When, however, the magnetic substance is subjected to a magnetic influence, the small molecular magnets are lined up, the north and south poles pointing in opposite directions.
11. *Magnetic induction* is the process of developing magnetism within a magnetic body by introducing it into a magnetic field.
12. *The earth* has magnetic properties like a bar magnet.
13. *Declination* is the name given to the angle a compass needle deviates from a true north and south line.
14. *Dip* is the name given to the angle the earth's magnetic field at any point makes with the horizontal.
15. *Permanent magnets* have many practical uses. Some of the most common are for compass needles, electrical meters, telephone receivers, etc.

CHAPTER II

ELECTROMAGNETISM

32. Introduction.—In the first chapter we learned that the space surrounding a permanent magnet possesses unique properties. Some of these properties became apparent when iron filings were sprinkled upon paper placed on the magnet. Other properties became apparent when a compass needle was brought near, and when the magnet was suspended so as to swing freely in a horizontal plane. It will be interesting to learn some of the prop-

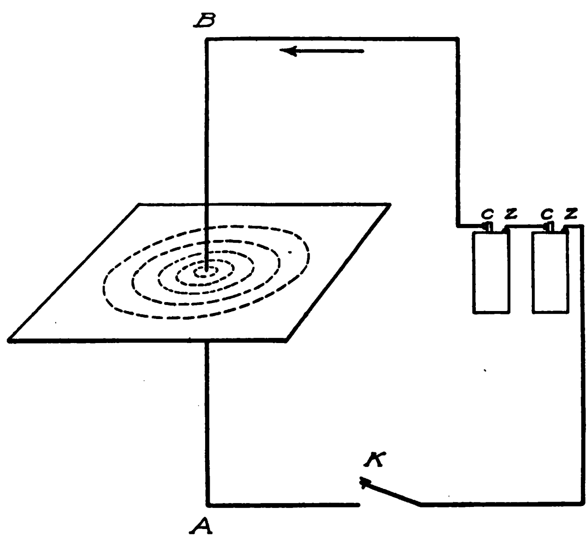

FIG. 20.

erties of wires carrying currents. The definition, determination, and laws of the electric current will be taken up later. At present we are concerned only with the properties of a current-bearing wire and the space near it when the wire is connected to the binding posts of an electrical cell, such as a dry cell, or other source of current. For brevity we shall call a wire along which an electric current is flowing, an electric wire.

33. Experiment 10. Magnetic Field around an Electric Wire.

Apparatus.—

A piece of cardboard
Three dry cells
Iron filings

Operation.—Connect three dry cells in series; that is, with a short piece of copper wire connect the carbon rod in the center of one cell with the zinc cup of the next cell, etc., as shown in Fig. 20. Arrange your apparatus so that part of the connecting wire *AB* shall pass through a piece of cardboard in a vertical direction. The cardboard must be horizontal. It is also advisable to have a key or switch *K* in the circuit. Hold the cardboard in a horizontal position and sprinkle some fine iron filings upon it. Iron filings that have been sifted through a cheesecloth will work best. Close the key *K* and gently tap the paper. Repeat this several times and draw a sketch of the arrangement of the iron filings around the wire. Next remove the paper and dip the electric wire in some iron filings. What do you observe upon removing the wire from the iron filings? Do any iron filings adhere to the wire?

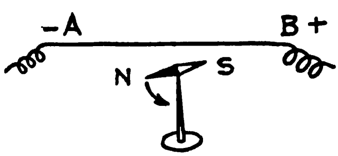

FIG. 21.

34. Experiment 11. Effect of Electric Current upon a Magnetic Needle.

Apparatus.—

Mounted magnetic needle or compass
Dry cell

Operation.—Connect the two binding posts of the dry cell by a copper wire and hold the wire above a magnetic needle as shown in Fig. 21. It is conventionally assumed that the current leaves the dry cell at the carbon terminal and enters at the zinc cup. These are called positive and negative electrodes, respectively. Hold the wire above the needle so that the current flows along the wire from south to north and note carefully the direction of the deflection of the needle. Hold the wire under the needle and let the current flow from north to south, and next hold it so that the current flows from south to north. In each case notice and record the direction of deflection of the north seeking end of the needle. Finally, hold the wire in a vertical position in front of

the north seeking pole of the needle and observe the direction of deflection when the current flows downward, and again when it flows upward. Repeat this experiment several times until the principles are thoroughly understood. Record your observations as follows:

Position of wire	Direction of current	Direction of deflection
Below..................	N. to S................	West..................
etc.....................	etc.....................	etc......................

35. Experiment 12. To Study Solenoids.

Apparatus.—Same as in experiment 11.

Operation.—With the apparatus is furnished a long coil of insulated wire. Connect the ends of this coil to a dry cell, as shown in Fig. 22. Hold one end of this coil, which is called a solenoid, near the north seeking pole of a magnetic needle. Is the needle attracted or repelled? Bring the other end of the solenoid near the same pole. Does the needle move toward or away from the solenoid? Try the experiment several times until you are certain that the magnetic needle is always deflected in the same direction when conditions are the same.

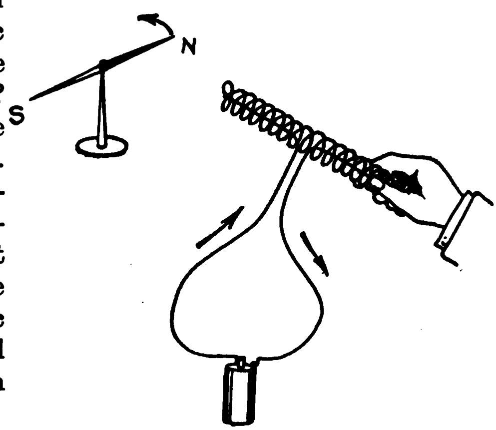

Fig. 22.

Change the solenoid and battery connections and again bring the ends of the solenoid near the compass needle. Observe carefully whether the compass needle is again attracted or repelled by the same end that attracted or repelled it before connections were reversed. Can you account for this?

Examine carefully the connections of the solenoid and note the direction in which the current flows when the needle is attracted and again when repelled. Draw a solenoid and mark on it the direction of current flow and north and south poles.

36. Theory.—The three preceding experiments are very important, for they show that current-bearing wire has all of the

properties of a magnet. In experiment 10 the student learned that the iron filings were arranged in circles around the wire. The cardboard really forms a cross-section of the field, and accordingly the field surrounding a straight wire may be looked upon as a series of concentric cylinders. The results of experiment 11 show that the field surrounding a current-bearing wire affects a magnetic needle, and that it is, therefore, magnetic. The results also show that the direction of the deflection of the needle is determined by the relative position of wire, needle and the direction of the current flow. The logical conclusion is, then, that the magnetic field around an electric wire has direction, and that this direction depends upon the direction of the current and the position of the wire. Reversing the current flow reverses the direction of the field.

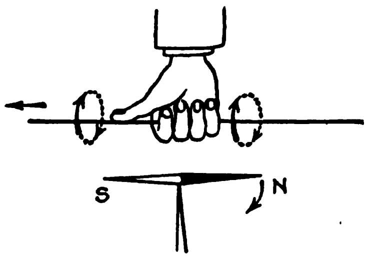

Fig. 23.

The direction of the field can always be determined by the following rule:

Grasp the wire with the right hand, the thumb pointing in the direction of the current; the fingers will then point in the direction of the magnetic lines surrounding the wire.

If the wire is near a magnetic needle, the north seeking pole will be deflected in the direction indicated by the fingers. This rule is illustrated by Fig. 23.

The results of experiment 12 show that a solenoid has the properties of a bar magnet, the two ends being of opposite polarity. That this must be so can easily be determined if the student will carefully consider what must take place when a current-bearing wire is wound into a circular coil, or solenoid. Since the direction of the magnetic lines is determined by the direction of the current, when the wire is coiled, the lines must enter at one end and leave at the other. The arrangement of the lines within a solenoid is shown in Fig. 24. It will be noticed that all of the lines do not go the full length of the coil, but many escape between the convolutions of the coil. The field within the solenoid is not uniform but grows weaker from the center toward the ends. The end from which the lines emerge is the north seeking pole, while the other end is the south seeking pole.

The polarity of the solenoid can readily be determined by the rule for determining the direction of the magnetic lines about a straight conductor. For if one of the convolutions or turns of wire be grasped by the right hand, as directed in the rule, the fingers will point in the direction of the north seeking pole of the solenoid. The same relation can, however, be expressed as follows: *If an observer face one end of a solenoid and the current flows in a counter-clockwise direction, the north seeking pole of the solenoid is nearer the observer. If the current flows in a clockwise direction, the south seeking pole is nearer the observer.*

37. Strength of Magnetic Field Around an Electric Wire.— The strength of a magnetic field is defined in terms of the force it exerts upon a unit magnet pole. Although it is impossible

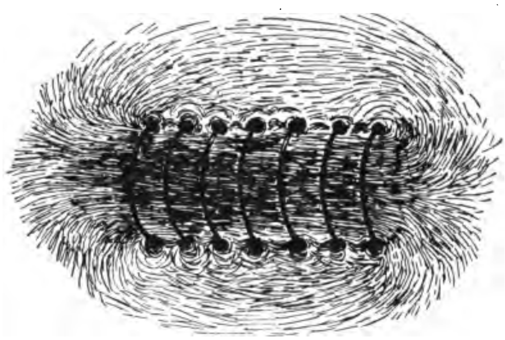

FIG. 24.

in practice to develop a single unit pole, nevertheless, theoretically a unit magnet pole is defined in Article 10. A magnetic field is said to have unit strength when it exerts a force of one dyne upon a unit magnet pole. Practically it is impossible to measure the strength of a magnetic field in this way.

Since iron filings are arranged in lines, magnetic fields are always described as though they consisted of lines, and a unit magnetic field is represented as consisting of one line per square centimeter, etc. The magnetic field due to an electric wire is likewise considered as though it were made up of lines wrapped around the conductor. The strength of the field will then be represented by the number of lines per square centimeter in a plane containing the wire. The density or number of lines per square centimeter decreases from the wire outward. Experi-

ments, as well as theory, show that the strength of a magnetic field at any point due to a current-bearing wire depends directly upon the current strength and inversely upon the average distance of the point from the wire. In algebraic symbols if H represents the field strength, I the current, and d the distance of a point from the wire, then,

$$H=\frac{2I}{d}=\frac{\text{twice current}}{\text{distance}}$$

EXAMPLES

1. A current of ten units flows through a straight wire. What is the magnetic field strength at a distance of 5 cm. from the wire?

Solution.—

$I=10$ units
$d=5$ cm.
Then $H=\frac{2\times 10}{5}=4$ units

2. A field of 5 units exists at a distance of 5 cm. from a given current-bearing wire. What is the field strength at a point 25 cm. distant from the wire?

Solution.—

$H_1=5$
$d_1=5$
$H_2=$ is unknown
$d_2=25$
Then $5=\frac{2I}{5}$
and $H_2=\frac{2I}{25}$

Dividing second equation by first we get $\frac{H_2}{5}=\frac{5}{25}$

Whence $H_2=\frac{25}{25}=1$ unit

This also follows from the relation given, increasing the distance 5 times decreases the field strength to 1/5; hence, 1/5 of $5=1$ unit.

38. Reaction between Electric Wires.—When two current-bearing wires are brought near each other, they will either be attracted or repelled if parallel, and if not parallel will tend to become parallel. The force of attraction or repulsion is due to the interaction of the two magnetic fields around the wires. The manner in which such a force develops will readily be understood from Figs. 25 and 26. If the two wires are parallel and the cur-

rents flow in the same direction, the magnetic fields will combine and encircle both wires and the two wires will be drawn toward each other. This is shown by Fig. 25.

When the two currents flow in opposite directions, the magnetic fields cannot combine as they are oppositely directed. The reaction between the fields will tend to push the wires farther apart. These conditions are represented in Fig. 26. It can be shown by higher mathematics that the force tending to draw the wires together, or to push them apart is proportional to the product of the currents in the two wires so long as the wires remain in fixed positions. For instance, if the current in one wire, Fig. 25, is 10 units, and in the other wire the current is 5 units, then the force pulling one toward the other is proportional to 5×10. Its exact value will depend upon the distance between the two

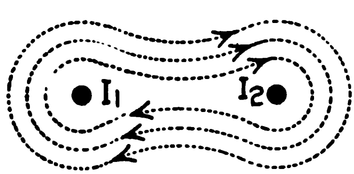

FIG. 25.

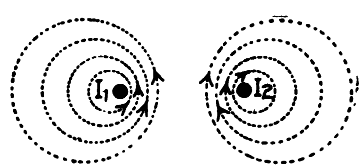

FIG. 26.

wires. This principle can be put into an algebraic equation, as follows:

Let I_1 = current in one wire.
I_2 = current in the other wire.

Then $F = K \times I_1 \times I_2$, where K is a proportionality factor whose value depends upon the distance between the wires. When the same current flows in the two wires, $I_1 = I_2 = I$, and the expression for the force becomes:

$F = KI^2$, which, in words, means that the force is proportional to the square of the current. This principle has numerous practical applications.

If two conductors are mounted in such a way that the force between them can be measured, the device can be used to measure the current flowing. Several electrical measuring instruments in practical use operate on this principle. The essential parts of the simplest instrument, known as the "electrodynamometer ammeter" are shown in Fig. 27, and an actual instrument is shown in Fig. 28. As shown, the operating part of the in-

strument consists of two coils, FF' and MM'. The former is rigidly attached to the vertical support as shown in Fig. 28, and the second can turn around a vertical axis. The current to be measured is passed into coil FF' through T_1 and after passing through FF' it enters M at C and finally leaves the movable coil at T. The student will observe that the current passes upward in the side F of the fixed coil and the side M of the movable coil. Likewise, it passes downward in F' and M'. According to the principle explained, the side M will be attracted by F and repelled by F', and, likewise, the side M' will be attracted by F' and re-

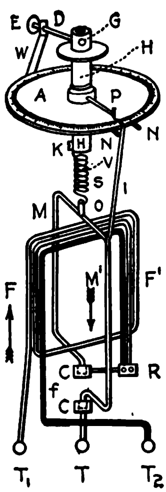

FIG. 27.

FIG. 28.

pelled by F. These forces of attraction and repulsion will cause the movable coil to be deflected. By turning the torsion head G, the movable coil is brought back to its original or zero position. The angle through which the torsion head is turned is a measure of the force tending to deflect the movable coil. Since, as has been pointed out, this force is proportional to the square of the current in the coils, the angle through which the torsion head is turned to bring coil MM' to its zero position is proportional to the square of the current. Hence, if we know what current is required to cause unit deflection, we can calculate the current. The movement of a Weston voltmeter is shown in

Fig. 29. The student will readily see that this instrument also operates upon the same principle.

39. Magnetic Field at Center of a Circular Coil.—The student has already learned that when a conductor is wound into the form of a long coil, and a current is passed through it, the solenoid has the properties of a bar magnet. Much the same principles hold in the case of a circular coil. The arrangement of iron filings within such a coil is shown in Fig. 30. The end of the coil where the lines enter has the properties of a magnetic south pole, and the other end those of a north pole.

FIG. 29.

We have already suggested a method of measuring a current by the interaction of the magnetic fields surrounding the conductors. In order to measure a current by its magnetic effect, it is necessary to determine some effect which shall be assumed to be unity. That is, the effect selected shall represent the unit used in measuring the current

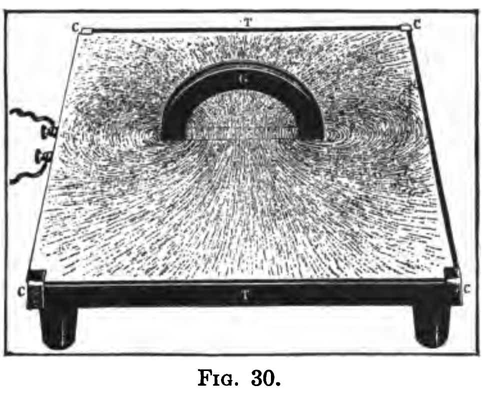

FIG. 30.

producing it. It is very evident that in selecting such a unit the effect must have a definite relation to the current. The simplest relation is where the effect is directly proportional to the first power of the current. Such a quantitative relation will be

explained later. Now we are concerned with the magnetic effect of the current.

When a current is sent through a circular coil, it develops a magnetic field at the center of the coil. The strength of this field is also directly proportional to the first power of the current, and in algebraic symbols we can express this relation thus: $H=\frac{2\pi I}{r}$ for a coil of one turn, where I is the current, π is 3.1416, r the radius of the circle, and 2π is 2×3.1416. The mathematical derivation of this formula is too difficult for an elementary text. For any given circular coil $\frac{2\pi}{r}$ is constant; and, accordingly, we have the relation mentioned, namely, that the strength of field H is directly proportional to the first power of the current.

EXAMPLES

1. **A circular coil of 5 cm. radius carries an electric current of 5 electromagnetic units. What is the field strength at the center of the coil?**

Solution.—

$$H=\frac{2\pi I}{r}$$
$$I=5$$
$$r=5$$
$$\text{Then } H=\frac{2\times 3.1416\times 5}{5}=6.28 \text{ gausses}$$

2. **What is the current which, when passed through a circular coil of 20 cm. diameter, develops a magnetic field of 2 gausses at the center of the coil?**

Solution.—

Solving the equation

$$H=\frac{2\pi I}{r} \quad \text{for } I \text{, we get}$$
$$I=\frac{Hr}{2\pi}$$
$$H=2$$
$$r=10$$
$$\text{Then } I=\frac{2\times 10}{6.28}$$
$$=\frac{20}{6.28}=3.1+ \text{ units}$$

40. Unit of Current.—The above relation together with the definition of unit magnet pole has been selected as the basis for defining unit current and is as follows: *A unit current is that*

current which, when passing through an arc of unit length in a circle of unit radius will produce at the center of the circle a magnetic field of unit intensity. In the system of units that has for its fundamental units the centimeter, second, and gram, the unit arc is an arc of 1 cm. the unit radius is 1 cm., and the unit magnetic field is one that exerts a force of 1 dyne upon a unit magnet pole. The electromagnetic unit of current can then be defined as that current which, when flowing through a conductor bent into a circle of 1 cm. radius, exerts a force of 2π dynes on a unit pole at the center of the circle of which the conductor is the circumference. The factor 2π is used because the circumference of a circle is $2\pi r = 2 \times 3.1416 \times r$, and when $r = 1$ cm., this reduces to $2\pi = 2 \times 3.1416$. If the current exerts a force of 1 dyne when flowing through an arc 1 cm. long, it will exert a force of 2π dynes when passing along an arc 2π cm. long.

This unit of current is too large for practical purposes and, therefore, one-tenth of this value has been taken as the practical unit of current, and is called an *ampere,* after the French physicist, Ampere. Later we shall learn how a current may be measured by its chemical effect.

The first practical instrument for measuring an electrical current was operated by the magnetic effect of the current. The instrument consisted of a small magnetic needle mounted at the center of a circular coil. The instrument has only an historical interest at present.

41. Electromagnets.—We have learned that a solenoid has the properties of a bar magnet. The poles of a solenoid are not, however, very strong and if we had to rely upon permanent magnets and solenoids only for magnetic fields, none of the large dynamo-electric machines would be possible. It is the combination of a solenoid, or coil of other form, and an iron core that gives the strongest magnetic field. This principle we shall now investigate.

42. Experiment 13. Development of Magnetism in an Iron Core by an Electric Current.

Apparatus.—

Solenoid
Dry cells
Compass needle
1/2-in. × 6-in. bar of iron
1/4-in. × 12-in. bar of iron

Operation.—Connect the solenoid and two dry cells in series. Place the solenoid and compass in the relative position shown in Fig. 4. The solenoid is to replace the bar magnet there shown. Move the solenoid either nearer to or farther from the compass until the compass needle shows a deflection of only one or two degrees. Mark on the table the position of the solenoid. Disconnect the solenoid and in the same position place the 1/2-in. × 6-in. iron bar. Again observe the direction and amount of the deflection of the compass needle. In case the bar has been previously magnetized and the compass needle is deflected in a direction opposite to that caused by the solenoid alone, turn the bar end for end and record the direction and amount of the deflection.

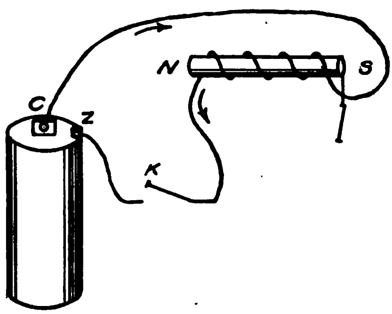

FIG. 31.

Having determined the influence of the bar and solenoid singly, connect up the solenoid as before and place it in its previous position. Place the bar within the solenoid and upon closing the circuit, determine the deflection of the compass needle. Is it greater than the sum of the deflections caused by the bar and solenoid separately?

Take some four-penny nails and determine how many will adhere to one end of the bar when the solenoid is excited by one dry cell. Then connect successively two and three dry cells in series, and in each case determine the number of nails that can be suspended from one end. A diagram of connections is shown in Fig. 31. Does the number of cells in series have anything to do with the strength of the electromagnet?

Place the electromagnet in a horizontal position and upon it in a horizontal position place a stiff sheet of paper. Excite the electromagnet by closing the key and sprinkle iron filings upon the sheet of paper. Draw a diagram showing the arrangement of the iron filings. Compare this diagram with the magnetic field of a bar magnet.

43. Experiment 14. Magnetic Properties of U-shaped Bar.

Apparatus.—Same as in experiment 13.

Operation.—Bend the 1/4-in. piece of iron into the shape of the letter U and wind each prong with about 20 turns of insu-

lated wire. The current must flow in opposite directions around the two prongs. Now connect two dry cells to the two free ends of the wire and test the electromagnet for polarity. Lay the electromagnet on a flat surface and place a sheet of paper upon it: close the electric circuit and sprinkle iron filings over the paper. Draw a diagram of the arrangement of the iron filings. Compare your diagram with the diagram of the magnetic field of a horseshoe magnet.

Place a large nail across the poles of the electromagnet. Is the nail held in place more firmly than when it was in contact with one end of the bar electromagnet? Hold the U-shaped electromagnet in an inverted position and break the electric circuit. What happens to the nail?

44. Theory.—All the foregoing principles are of the utmost importance in the industrial application of electricity. It was Joseph Henry, at one time professor of physics at Princeton University, who discovered the effect an electric current has upon a soft-iron bar.

At the present time we can easily make the simple experiments which show the electromagnetic effect of the current, but when Professor Henry made his experiments no insulated wire was available. The difficulty of the task is at once apparent. Furthermore, no one at that time had the slightest notion as to how important his discoveries were. In the Library of Congress at Washington statues are arranged around the reading room balcony, each figure symbolizing important advancement in some line. A statue of Joseph Henry with a small electromagnet in his hand is used to symbolize the most important development in electromagnetism.

The results of experiments 13 and 14 show only a few of the effects and relations between an electric current and magnetism. Others will be studied later. The important principles developed are the fact that a current passing around an iron bar makes a magnet of the bar, and that the magnetic strength increases with the current and number of turns of wire around the iron core.

It has also been shown that the electromagnet is much stronger than a permanent magnet of the same size. The electromagnet is, however, only a temporary magnet, as the experiments show that when the electric circuit was broken the iron core lost its magnetism.

45. Magnetic Field Inside of a Long Solenoid.—Although it is somewhat difficult to determine the mathematical expression for the strength of the magnetic field inside of a long solenoid, nevertheless, the expression is necessary for the purpose of calculation. It can be shown that if the length of the coil is not less than 20 times its diameter, the field at the center of the solenoid is practically uniform, and that its value is given by

$$H = 0.4\pi nI = 1.257\ nI \text{ gausses,}$$

where n is the number of turns per centimeter length of coil, and I is in amperes.

This equation also holds for solenoids, bent so as to form a closed ring. The magnetic field produced by a ring solenoid is confined entirely to the closed space inside the spiral forming the ring.

EXAMPLE

A solenoid of 1,000 turns is 20 cm. long. What is the magnetic field near the center of the solenoid, when 10 amperes are flowing through it?

Solution.—

$$H = 1.257\ nI$$
$$n = \frac{1000}{20} = 50$$
$$I = 10 \text{ amperes}$$
$$\text{Then } H = 1.257 \times 50 \times 10$$
$$= 628.5 \text{ gausses}$$

46. Permeability.—In experiment 13 the student learned that when a soft-iron core is placed within a solenoid, the resulting magnet is much stronger than when the core is omitted. The iron possesses the property of increasing the magnetic field strength. The magnetic lines are concentrated within the iron core and radiate from the ends. If we express the strength of a magnetic field within the solenoid without iron by H, and if B represents the strength of the magnetic flux within the iron core when it is subjected to the magnetic influence of the solenoid, then the ratio of B to H is called the permeability. This ratio is usually expressed by the Greek letter μ (*mu*). Algebraically this ratio is given by

$$\mu = \frac{B}{H}$$

EXAMPLE

A certain specimen of iron, when subjected to the magnetic influence of a solenoid capable of creating in air 50 magnetic lines to the square centimeter, was found to be permeated with 20,000 magnetic lines per square centimeter. What is the permeability of the iron?

Solution.—

According to the definition, permeability, $\mu = \frac{B}{H}$

$$B = 20{,}000$$
$$H = 50$$
$$\text{Hence, } \mu = \frac{20000}{50} = 400$$

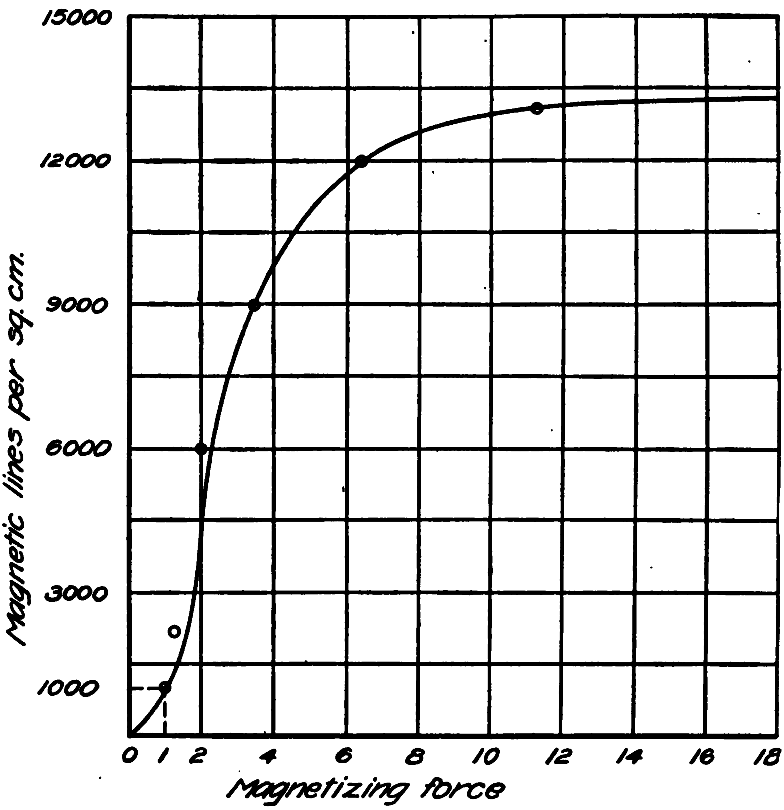

FIG. 32.

This is a low value, for a good iron may run as high as 10,000. The exact value of the permeability depends greatly on the quality of the iron and its previous magnetic history, and also

upon the degree of magnetization. The permeability of soft wrought iron is greater than that of cast iron; and that for mild or open hearth steel, as now made for electrical machinery, is in some cases equal to that of the best soft wrought iron.

The results of the two previous experiments do not show clearly the dependence of the magnetic strength upon the strength of the current, because the experiments are only illustrative. When, however, the experiments are performed in such a way that the current as well as the magnetic flux are measured, it is found that when the current is very weak and the number of turns on the core are few, the magnetism in the iron core is low. When the current strength has reached a certain value, the magnetic flux increases greatly for a small increase in current. Beyond this point the magnetic flux increases again slowly. This variation in flux with the magnetizing current is shown in Fig. 32. In order that the student may understand the curve, an explanation of plotting curves will be given. Curves showing the relation between the variations of two quantities which are mutually dependent are of extreme importance in all engineering work.

47. Curve Plotting.—Where the value of one quantity depends upon, or varies with another quantity, the character of the variation is most clearly shown by means of a continuous line or curve which is determined in accordance with the following principles:

First, two lines or axes XX' and YY' are drawn at right angles to each other, Fig. 33. These two axes divide the plane into four parts called quadrants, which are numbered *I*, *II*, *III*, *IV* in the figure.

A point is located on a plane when its distances from the axes are known. The distance of the point from the axis YY' is called its x-distance, or abscissa; its distance from the axis XX' is called its y-distance, or ordinate. The two distances taken collectively are called coordinates of the point.

48. Signs of the Coordinates.—For purposes of uniformity mathematicians have agreed that distances measured to the right of YY' are to be called positive; those to the left negative. Distances measured above axis XX' are positive; those below, negative. Thus, a point in the first quadrant has both coordinates positive. The coordinates of a point in the third quadrant are both negative. The second quadrant, the abscissa, is nega-

tive and the ordinate positive, while in the fourth quadrant the abscissa is positive and the ordinate negative. These are shown in Fig. 33.

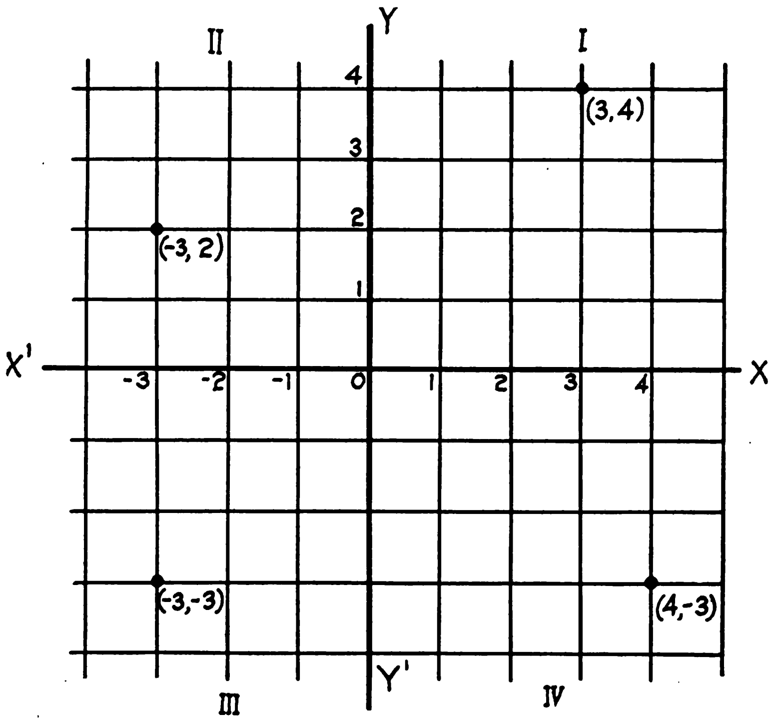

FIG. 33.

49. Plotting.—The locating of a point by means of its coordinates is called plotting the point. To locate a point whose coordinates are (4, 5), which means that $x=4$, $y=5$, we measure from the origin, O, to the right on OX four units, and then from this point we measure up 5 units parallel to OY. The point thus reached is the point (4, 5). Any other point is located in the same manner.

In the figure are shown the following points (3, 4), (−3, 2), (−3, −3), (4, −3).

In determining a line or curve which shows the variation of one quantity with reference to another, we first locate several points and through these draw a smooth curve.

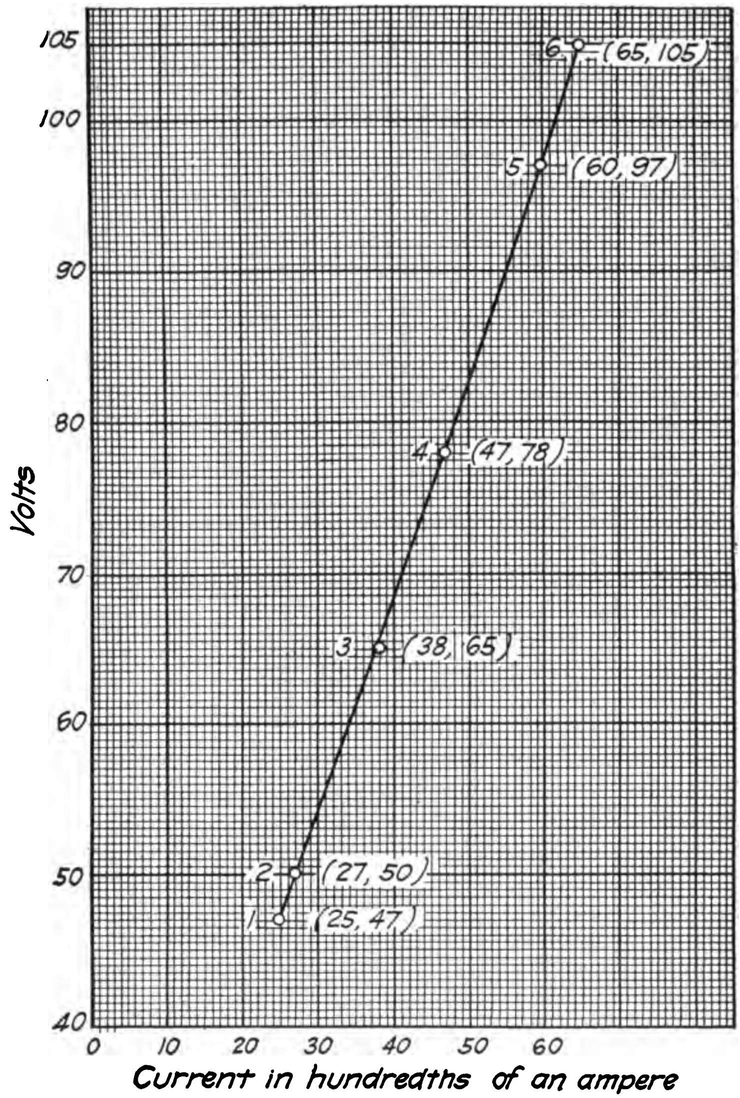
105
100
90
80
70
60
50
40
Volts
6 (65, 105)
5 (60, 97)
4 (47, 78)
3 (38, 65)
2 (27, 50)
1 (25, 47)
0
10
20
30
40
50
60
Current in hundredths of an ampere

FIG. 34.

EXAMPLE

The current taken by a 110-volt 16-candle-power lamp at different voltages was measured with the following results:

Volts	Amperes	100×amperes
47	0.25	25
50	0.27	27
65	0.38	38
78	0.47	47
97	0.60	60
105	0.65	65

To determine whether the current increases uniformly with the voltage we plot a curve as shown in Fig. 34. Point 1 is determined by counting to the right 25 units (100 times current), and up 47 units (the voltage where the current is 0.25). The other points are located exactly the same way. The line joining points 1 and 6 is practically a straight line. If the voltage had been reduced to zero, that is, if the current corresponding to voltages less than 47 volts had been determined, the curve would no longer be a straight line.

50. Magnetomotive Force, or Magnetizing Force, of a Solenoid.—The magnetizing effect of an electrical current depends not only upon the current strength, but also upon the number of turns in the coil. This fact can easily be shown by changing the number of turns on a solenoid, while the current is maintained constant. A current of 10 amperes flowing through a coil of 100 turns has the same magnetizing effect as a current of 5 amperes in 200 turns or 1 ampere in 1,000 turns. The exact numerical value of the magnetizing force, called magnetomotive force, depends upon the units used. Since a unit magnet field has been defined as the field which exerts a force of one dyne upon a unit magnet pole, the magnetomotive force of a coil is measured by the work expended in moving a unit magnet pole around the magnetic circuit. Thus in Fig. 35, if P represents a unit magnet pole, the magnetomotive force of the solenoid will be measured by the work expended in moving P around the dotted line against the magnetizing force. It can readily be shown that the magnetomotive force is given by

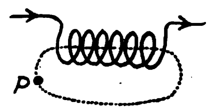

FIG. 35.

$$M.M.F. = 0.4\pi NI$$

where $\pi = 3.1416$

N = number of turns

I = current in amperes

The product NI is called *ampere-turns*, and $0.4\pi = 1.257$. Hence, the magnetomotive force is equal to

$$M.M.F. = 1.257 \times \text{ampere turns.}$$

The unit of magnetomotive force is called a *gilbert* after the physician of Queen Elizabeth.

EXAMPLE

How many gilberts will a current of 15 amperes develop in a coil of 2,500 turns?

Solution.—

$$\begin{aligned} M.M.F. &= 1.257\ NI. \\ N &= 2{,}500 \\ I &= 15 \text{ amperes} \\ NI &= 37{,}500 \\ M.M.F. &= 1.257 \times 37{,}500 \\ &= 40852.5 \text{ gilberts} \end{aligned}$$

With these explanations in mind we can understand the manner in which the curve, Fig. 32, is plotted, and also its significance. A coil of several turns is wound around an iron ring. In series with the coil and a source of current is connected a regulating rheostat for adjusting the current. The current is measured, and then according to the above example, the magnetizing force is calculated. The current is next changed and again measured. Every time the current is measured the magnetic flux in the iron ring is determined. The number of magnetic lines per square centimeter are then plotted vertically while the corresponding magnetizing force causing them is plotted horizontally Through the points thus determined a smooth curve is then drawn. The curve shows that for low values of the magnetomotive force the number of magnetic lines increases slowly. Between the values of one and four gilberts the increase is quite rapid, and above that value the ratio of magnetic lines to magnetomotive force decreases rapidly. The permeability of iron is evidently not constant. If the permeability were constant, the magnetization curve would be a straight line. A knowledge of the magnetic properties of iron is of very great importance in the design of electrical machinery.

51. Magnetic Hysteresis.—In discussing the molecular theory of magnetism it was pointed out that when a bar is magnetized, all or nearly all of the molecules have been lined up with their

north ends pointing in one direction and their south ends pointing in the other direction. A diagram to illustrate this assumption is shown in Fig. 13. When the bar is magnetized by an electric current, or, in fact, in any other way, some energy must be spent in forcing or compelling the molecules to line up. In

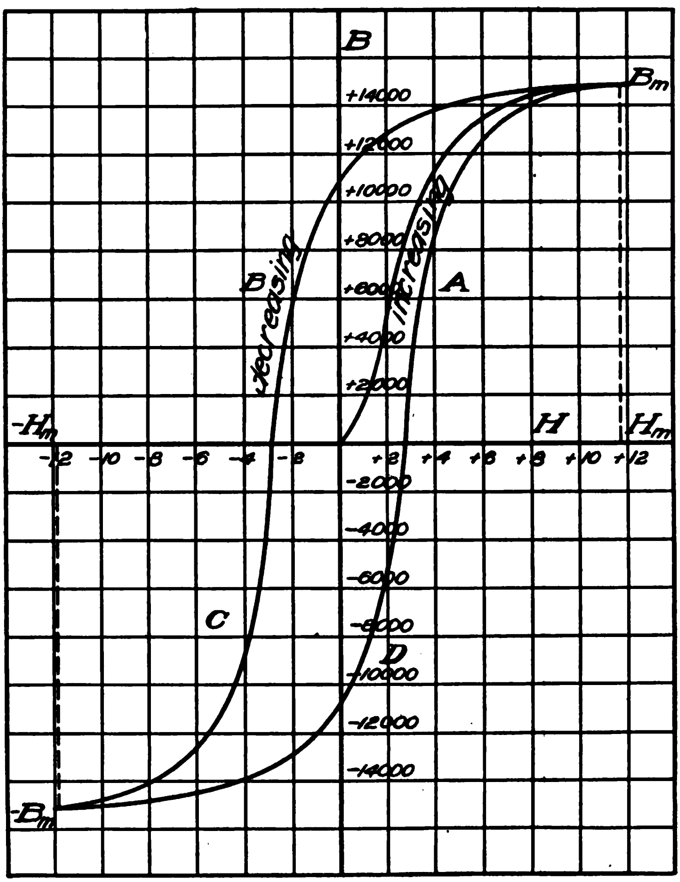

FIG. 36.

magnetizing by direct current, this energy is supplied in the first fraction of a second, and after the molecules have lined up, or the bar has become magnetized, no more energy is spent in overcoming the "frictional resistance" of the molecules. If all of the molecules are not lined up, an increase in the current will make more of them to fall in line and this will go on until all

have been turned in one direction; any additional current has no effect, and the iron is said to be saturated. For practical purposes the sample of iron for which the curve is shown in Fig. 32 may be considered saturated at any point above the sharp bend or knee. That is, above 12,000 lines per square centimeter. If, after having reached a certain value, the magnetomotive force is gradually decreased and if, when the current reaches zero, it is reversed and increased gradually in the opposite direction to the same maximum value as before, the magnetization curve will not decrease along the same line as it increased, but will remain higher. This is shown in Fig. 36. When the magnetizing force has dropped to zero, the flux density is still about 10,800 lines per square centimeter. This value is called remanent or residual magnetism. The flux density drops to zero only after the magnetizing force has been reversed and, in the illustration shown, reached a value of about three gilberts in the opposite direction. The magnetizing force required to reduce the residual magnetism to zero is called *coercive force.* It is thus evident that work must be done in causing the molecules to turn around and point in the opposite direction. The decreasing values of the flux density lag behind the values corresponding to the increasing values of the flux density. This lagging behind has, therefore, been given the name *hysteresis* which means "lagging behind," and the area bounded by the four lines A, B, C, and D is called a hysteresis loop. This loop is due to the fact that some work must be done in magnetizing the iron first in one direction and then in the other direction. The wider the loop the greater the amount of energy spent in the process of reversing the magnetization. This energy appears as heat in the iron, and is lost for all practical purposes. For electrical machines in which the magnetization is variable, it is of great importance to use iron whose hysteresis loop is very narrow and consequently has small hysteresis loss.

RECAPITULATION

1. *Electromagnetism* is the principle of developing magnetism by means of an electric current.
2. A *solenoid* is a helical coil of wire of many turns, usually of circular cross-section. The field intensity within a long solenoid is equal to $H = 0.4\pi nI$, $n =$ number of turns per centimeter.
3. When two current-bearing wires are parallel, they are attracted

when the currents flow in the same direction, and repelled when the currents flow in opposite directions.

4. To determine the direction of the magnetic lines around a current-bearing wire, grasp the wire with the right hand; if the thumb points in the direction of the current flow, the fingers will point in the direction of the magnetic lines encircling the wire.
5. The *strength of a magnetic field* at any point near an electric wire increases directly as the current and inversely as the distance of the point from the wire; thus:

$$H=\frac{2I}{d}$$

6. The reaction between the two coils of an electrodynamometer ammeter is proportional to the square of the current; thus:

$$\text{Deflection} = KI^2$$
$$\text{Whence } I=\sqrt{\frac{\textit{deflection}}{K}}$$

7. The magnetic field at the center of a circular coil is also proportional to the current strength and inversely as the radius; thus:

$$H=\frac{2\pi I}{r}$$

8. The *absolute electromagnetic unit of current* is that current which, when flowing in a conductor bent into the circumference of a circle of unit radius, exerts a force of 2π dynes upon a unit magnet pole at the center of the circle. This unit is ten times as large as the practical unit called the ampere.
9. An *electromagnet* is a solenoid with an iron core.
10. *Permeability* is the property of iron that causes it both to concentrate and to increase the number of magnetic lines inside of a coil or solenoid when placed within. Numerically it is the ratio of the flux density to the field strength; thus,

$$\mu=\frac{B}{H}$$

11. The *magnetomotive force* of a solenoid is proportional to the product of the total number of turns by the current. Numerically it is given by

$$M.M.F.=0.4\pi\ NI.$$
$$=1.257 \text{ ampere turns}$$

The unit of magnetomotive force is the *gilbert;* or the ampere turn, which is the magnetomotive force produced by a current of one ampere in one turn of wire.

12. *Hysteresis* is the lagging of the magnetic flux behind the magnetizing field. A *hysteresis loop* is the area bounded by curves showing the relation between the magnetic flux and the magnetizing field. *Hysteresis loss* is the energy wasted or converted into heat in alternately magnetizing iron. The area of the loop is proportional to the loss.
13. *Residual or remanent magnetism* is the flux that remains in the iron core after the magnetizing field has dropped to zero.
14. *Coercive force* is the value of the magnetizing field which is required to reduce the remanent magnetism to zero.

CHAPTER III

SOME PRACTICAL APPLICATIONS OF ELECTROMAGNETS

In the preceding chapter it was shown that when an electric current flows around an iron core, the iron core becomes a strong magnet. In this chapter we shall take up some of the practical applications of this principle.

52. Experiment 15. To Study the Construction and Operation of the Electric Bell.

Apparatus.—

Electric bell
Push-button or switch
Connecting wires
Dry cell

Operation.—Connect one dry cell, bell, and switch in series as indicated in Fig. 37. In this diagram the standard symbol for a cell is used. The short line represents the negative or zinc electrode, and the long line the positive or carbon electrode.

If one cell will not cause the bell to ring when the circuit is closed, connect two cells in series in the circuit; close the circuit and observe the sparks at the point where the spring to which the clapper is attached touches the point of screw *P*. The current crosses at this point; hence the circuit is broken whenever the spring leaves the screw. Trace the circuit through the bell from one binding post to the other. The metal frame or base of the bell usually forms part of the circuit. Does it in this bell? There are four posts that must be examined carefully. They are the two binding posts, the post that carries the screw *P* and the upright to which the clapper is attached. One or more of these will be found to be electrically insulated from the base by means of hard-rubber or fiber washers. Such a post does not make electrical contact with the base, and the electrical current cannot pass between them. The current is thus compelled to follow a definite course through the winding and base. Draw a simplified diagram showing this course and describe it. Mark the insulated posts in this diagram, and represent by a dotted line the path of the circuit formed by the metal base of the bell.

Examine the winding on the electromagnet and determine if the two parts are wound in the same direction. What is the purpose of the iron core? Why is there an iron yoke across the ends of the cores at *A*? Is the enlargement of the clapper stem, *S*, of soft iron, brass, or hard steel? How can you tell? This part of the stem is called the armature. Why does not the armature remain in contact with the iron cores when drawn up? Are the two exposed ends of the electromagnet core of like or unlike polarity? How can you tell? Explain the action of the bell. How would the bell behave if the circuit were such as to send the current through the electromagnet without crossing between the screw and spring? Try this by connecting a piece of wire between *P* and *S* so that it remains in contact with *P* and *S* all the time. Does the bell continue to ring?

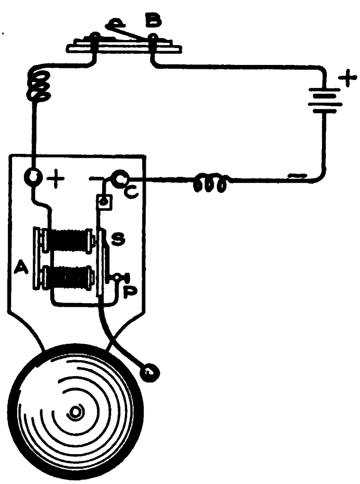

FIG. 37.

If you have two electric bells connect them in series; that is, connect a binding post of one bell to a binding post of the other bell and connect the battery to the two free binding posts, one on each bell. Close the circuit; do the bells ring? Do they ring as when used singly? If you think the trouble is due to weak current, put more batteries in the circuit. Explain. Connect the two bells in parallel; that is, take two wires and connect the two binding posts of the bell in circuit to the two binding posts of the second bell. Close the switch and note results. Do the bells ring better than when connected in series? Explain.

53. The Telegraph.—The fundamental principles of the operation of the telegraph are almost exactly the same as those of the electric bell. To make this clear the student should perform the following experiment.

54. Experiment 16. To Study the Principles of the Telegraph.

Apparatus.—Same as in preceding experiment.

Operation.—Connect the apparatus as in Fig. 37. Connect the binding posts C and P together by means of a piece of wire.

Close the electrical circuit by touching together the ends of the wire and observe the behavior of the clapper. Make and break the circuit rapidly. What is the result? Can such a device be used to signal at some distance?

55. Theory.—It is evident that when the circuit is closed at short intervals these short intervals may be represented by dots and the long intervals may be represented by dashes. Thus three short, or rapid strokes followed by three long and three short strokes may be represented thus · · · – – – · · · which is the international wireless telegraph distress signal. In practice many modifications of the simple apparatus must be made in order that the signals may be transmitted easily and rapidly, and for long-distance transmission. It must be evident that if two such bells are connected to the same circuit some

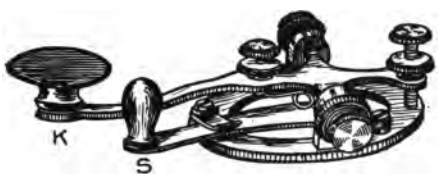

FIG. 38.

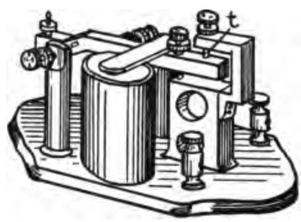

FIG. 39.

distance apart and each is provided with a make and break key, signals can be transmitted between the two stations. For instance, if one key is kept closed, making and breaking the circuit at the other station will operate the bell at the distant station. To facilitate the making and breaking of the electrical circuit a special key must be used. This key is shown in Fig. 38. The key is so constructed that every time the lever *K* is pressed down a current is sent over the wire. When the key is not in use in forwarding messages, the switch *S* short circuits the lever *K* so that messages can be received. At each end of the line, the bell is replaced by a properly mounted electromagnet called a sounder. This operates on exactly the same principle as the bell with the wire connection between posts *C* and *P*. In place of the bell the sounder is mounted on a resonant base, and the stop, which corresponds to the clapper in the bell, strikes a metal anvil, *t*, Fig. 39, giving forth a metallic click.

It is not practical to send signals over long distances with

the simple circuit described, on account of the small current. To overcome this defect, the line current is used merely to open and close a secondary circuit which consists of a battery and sounder. The opening and closing of the secondary circuit is accomplished by means of another form of electromagnet called a relay. Such an instrument is shown in Fig. 40. The electromagnet of the relay is magnetized by the line current while the

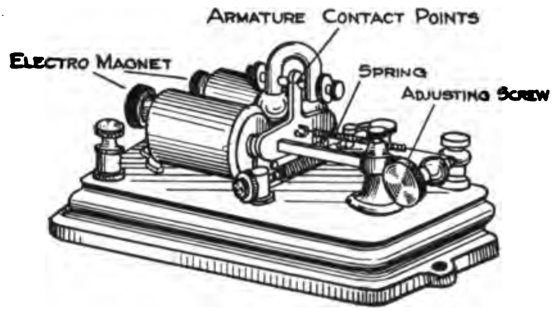

FIG. 40.

armature of the electromagnet acts as a key in the local battery circuit, closing and opening the circuit every time the main circuit is closed or opened. The manner in which this is done will be understood readily from Fig. 41. In this diagram a and a' are the two line wires connected to the electromagnet of the relay. As the electromagnet is energized the armature is at-

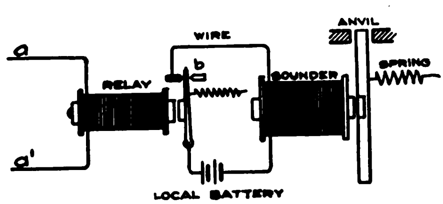

FIG. 41.

tracted, closing the local battery circuit at b. The sounder is then operated by the current from the local battery and the click may be made as loud as desired.

Fig. 42 is a diagram showing how the principles just explained are carried out in practice. At each station is a circuit consisting of a local battery, the sounder electromagnet, and the armature of the relay the electromagnet of which is in the line circuit.

The ground is used as one side of the line. If La Crosse wishes to call Milwaukee, the switch S at La Crosse is opened as indicated. By closing and opening the key at La Crosse the relays at both Madison and Milwaukee will operate, but since each station has its own signal, Milwaukee alone will answer. The armature P of the Milwaukee relay operates in unison with the key at La Crosse, and as a consequence the local circuit at Milwaukee is opened and closed and the sounder clicks at the will of the La Crosse operator.

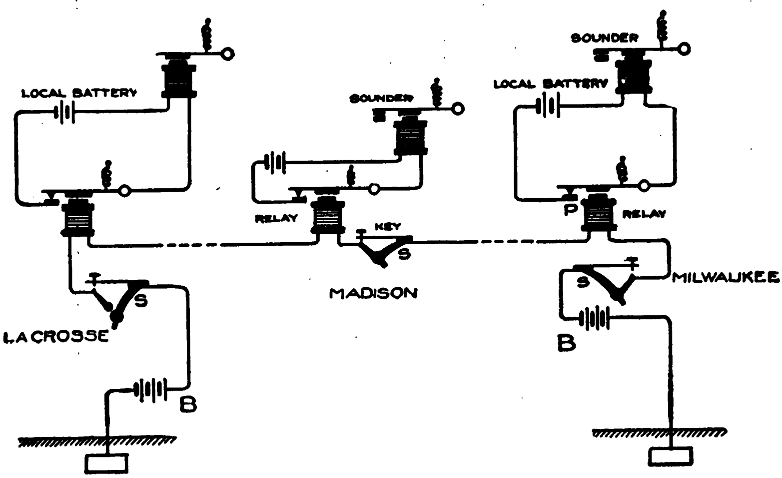

FIG. 42.

56. The Telephone.—The principles of electromagnetism are also used in the transmission of speech by telephone as well as by telegraph. The operation of the telegraph depends almost wholly upon the magnetizing property of an electric current while several other principles enter into the operation of the telephone. Only the application of the principles of electromagnetism will be pointed out and explained.

57. Experiment 17. To Study the Principles of Telephone Receivers.

Apparatus.—

Telephone receiver
Iron filings
Dry cell

Operation.—Unscrew the cap from the large end of the tele-

PLATE 2.—Switchboard, Wis. Telephone Co., Baraboo, Wis.

PLATE 3.—Terminal room, Wis. Telephone Co., Baraboo, Wis.

PLATE 2.—Switchboard, Wis. Telephone Co., Baraboo, Wis.

PLATE 3.—Terminal room, Wis. Telephone Co., Baraboo, Wis.

phone receiver. Under this cap you will find an enameled iron disk resting on a metal ring. Remove this disk. Why does it stick in place? Touch the ends of the pole pieces with the edge of the disk. What do you discover? Take hold of the iron ring and withdraw the magnet from the casing. This receiver is purposely constructed so that it can be taken apart easily. Take the bar magnet and determine which parts are magnetic and which are non-magnetic. Examine the winding about the pole pieces. Draw a sketch of the magnetic and electric circuit.

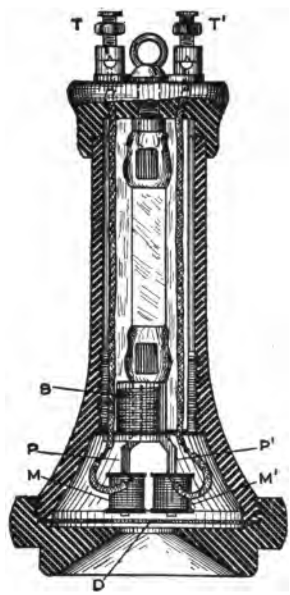

Fig. 43.

Replace the magnet within the receiver and hold it vertically with the large end up. Place a piece of cardboard or stiff paper over the pole pieces and sprinkle some iron filings on top of this. Gently tap the paper and observe the arrangement of the iron filings. Are the pole pieces like or unlike? Sketch the resulting magnetic field. Replace the diaphragm and cap. Connect one end of the receiver cord to one binding post of a dry cell, and while holding the receiver near the ear, touch the other binding post of the dry cell with the other end of the cord. What causes the click in the receiver? Make and break the circuit rapidly; what do you hear?

58. Theory.—The preceding experiment shows only that the essential principles of a telephone receiver are the superposition of an electromagnetic field upon a permanent magnet field. Fig. 43 shows the essential features of a very common bi-polar receiver. The shell is of hard rubber and is in three parts. Two permanent bar magnets are employed, the two being fastened together at one end and thus forming practically one magnet of the horseshoe form. To the other ends of the bar magnets are fastened two soft-iron pole pieces *P* and *P'*. Each of these pole pieces is wound with a coil of fine insulated copper wire, marked *M* and *M'* in the figure. Immediately in front of the pole pieces is fixed a sheet-iron diaphragm, *D*. The diaphragm forms a part of the magnetic circuit; where the mag-

netic lines enter the diaphragm a south pole is induced, and where they leave a north pole is formed. Thus the diaphragm acts as an armature and is bent or dished toward the pole pieces.

The coils on the pole pieces are wound in opposite directions, so that when a current flows in them in one direction they strengthen the field of the permanent magnet, and when a current flows in the opposite direction, the permanent magnet field is weakened. This strengthening and weakening of the magnetic field causes the diaphragm to vibrate. When the field is strengthened, the diaphragm is drawn nearer to the pole pieces, and when the current ceases the diaphragm springs back to its normal position. When the current in the coils opposes the permanent magnetic field, the diaphragm springs still farther away from the pole pieces and when the current ceases it again resumes its position as determined by the attraction of the permanent field. It is thus evident, that if the current flows in the coils first in one direction and then in the other, or if an alternating current flows in the receiver coils, the diaphragm will respond to every impulse of the current, no matter from which direction it comes.

If the receiver were not equipped with a permanent magnet, a magnetic field would be formed, no matter in which direction the current flowed. The diaphragm would be attracted or drawn in toward the pole pieces in either case, and would spring back to its neutral position when the current ceased to flow. The diaphragm would thus vibrate twice as rapidly as when a permanent magnet is used.

Then, again, the successive strengthening and weakening of the permanent magnet field permits or causes the diaphragm to vibrate through a greater space than would be the case if a soft iron core were used.

In a complete telephone circuit there are other electromagnets, but these will not be explained at this time.

59. Lifting Magnets.—The usual method of hoisting or lifting heavy, irregular shaped pieces of iron is rather inconvenient sometimes. For instance, large bundles of sheet iron, or bars of pig iron, are extremely difficult to lift by means of a hook and chain. The lifting magnet overcomes this difficulty. Fig. 44 shows a large lifting magnet hoisting some pig iron. The manner in which such a magnet is excited or magnetized will be understood readily from Fig. 45, which shows a cross-section of a

FIG. 44.

Cutler-Hammer lifting magnet. The essential feature of the magnet is a hollow steel casing around the central portion of which is wound a coil, *C*, of strap copper insulated with mica and asbestos. The two ends of the coil are brought out through a piece of armored hose at *A* and *B*. Direct current only is used for excitation. The current flowing through the coil magnetizes the steel casing in such a manner that the central portion is of one polarity and the outer rim of the opposite polarity. The cross-section can thus be represented by two horseshoe magnets with the two like poles placed together within a circular coil, while the other two poles are outside. The piece of iron that is lifted acts as the armature or keeper. The traction or lifting power of such magnets is very high when the size of the magnet is considered.

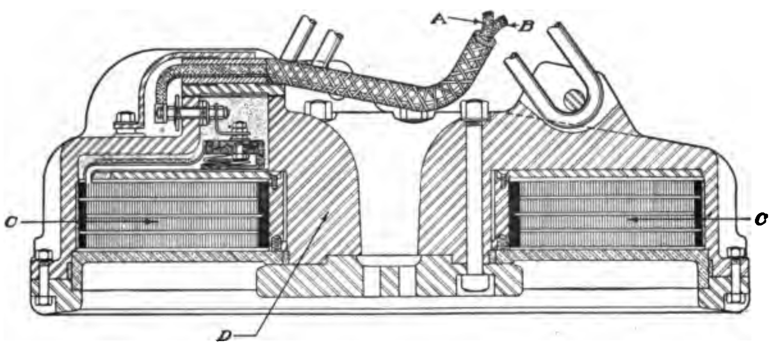

FIG. 45.

Lifting magnets are made of different shapes according to the purpose for which they are intended. Where large sheets, such as boiler iron or sheet iron, are to be lifted, the electromagnets are made with several short projecting poles each wound with a magnetizing coil. For carrying scrap iron or pig iron of irregular form, electromagnets are made with long projecting poles, which may be sunk into a heap of the iron. The pieces will stick to the poles on all sides.

60. Lifting Force of Electromagnets.—The lifting power of an electromagnet depends not only upon its construction and on the exciting current, but also upon the form of the piece to be lifted, and upon the quality of the iron in it. This is because the magnetic flux is closed through the piece to be lifted; hence the properties of the piece to be lifted determine the flux values.

Assuming that the piece to be lifted is made of the same material as the core of the lifting magnet, and that its cross-section is equal to that of the magnet core, the general principles of electromagnet design can be given readily. It can be shown by experiment and by higher mathematics that the force of attraction between two magnetized pieces of iron is proportional to the square of the flux density; that is, to the square of the number of magnetic lines per square centimeter. Thus, if in Fig. 46 the flux density be represented by B, the force tending to draw the two pole pieces together is proportional to B^2. If the cross-

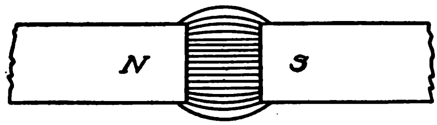

FIG. 46.

sectional area of the magnetic field in a plane perpendicular to the paper is S square centimeters, the force tending to draw the two poles together is proportional to the area S times the square of the flux density, or, in algebraic symbols,

$$\text{Force} = \frac{SB^2}{8\pi} \text{ dynes.}$$

This, of course, is on the assumption that the flux density, B, is uniformly distributed over the pole faces.

EXAMPLE

How many dynes of force will an electromagnet exert if its area of contact is 20 sq. cm. (3.1 sq. in.), and if it is magnetized to a flux density of 7,000 lines per square centimeter?

Solution.—According to the formula the force is given by

$$F = \frac{\text{Area} \times B^2}{8\pi}$$

$$\begin{aligned} \text{area} &= 20 \text{ sq. cm.} \\ B &= 7{,}000 \\ \pi &= 3.1416 \\ \text{Then } F \text{ (dynes)} &= \frac{20 \times 7000 \times 7000}{8 \times 3.1416} \\ &= 38{,}993{,}000 \text{ dynes (nearly)} = 87.6 \text{ lb.} \end{aligned}$$

In this country the English system of units is more commonly used in practice, and accordingly it is advisable to transform the above formula to these units. In practice the area of con-

tact, S, is usually given in square inches and the flux density B is given in lines per square inch. The manner of transforming the equation in which metric units are used into one in which the English units are used will be understood readily by reference to Fig. 47, which represents a surface of 1 sq. in. at right angles to a magnetic field. The dots are assumed to represent the magnetic lines. To change an area that is expressed in square inches to square centimeters it is only necessary to multiply the number of square inches by 6.452 as there are 6.452 sq. cm. in 1 sq. in.

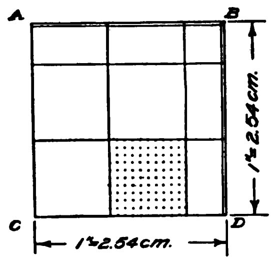

FIG. 47.

If the flux density is expressed in lines per square inch, the number of lines per square centimeter is obtained by dividing by 6.452. Thus if the area is S square inches, and the flux density is B lines per square inch, the expression for force in dynes becomes

$$F=\frac{6.452S\times\left(\frac{B}{6.452}\right)^2}{8\pi}\text{ dynes}$$

To change this to pounds divide by 444,793 = 445,000 nearly. We then get

$$F(\text{pounds})=\frac{6.452S\times\left(\frac{B}{6.452}\right)^2}{444793\times8\pi}$$

$$=\frac{6.452\times S\times B^2}{6.452\times6.452\times444793\times8\times\pi}$$

$$=\frac{S(\text{sq. in.})\ B^2\ (\text{per sq. in.})}{6.452\times444793\times8\times\pi}$$

$$\text{Force}=\frac{S(\text{sq. in.})\times B^2(\text{per sq. in.})}{72126000}$$

The student must remember that in the above equation S is in square inches, and B is the flux density per square inch.

EXAMPLE

What weight will an electromagnet lift whose area of contact is 1.66 sq. in., and flux density is 83,850 lines per square inch?

Solution.—

$$F=\frac{SB^2}{72126000}$$
$$S=1.66 \text{ sq. in.}$$
$$B=83{,}850$$
$$F(\text{pounds})=\frac{1.66\times 83850\times 83850}{72126000}$$
$$=161.8 \text{ lb.}$$

The student will readily see that this is a small magnet, as the area of contact is only 1.66 sq. in.

61. Traction and Magnetizing Force.—Summarizing some of the principles of the magnetic circuit so far discussed we have:

S = Cross-sectional area
l = Length of magnetic circuit in centimeters
H = Magnetic field within solenoid without iron
B = Flux density or number of lines per unit area within iron core placed in the solenoid
$\mu = \text{permeability} = \frac{B}{H}$

Magnetizing force of solenoid $M.M.F. = 1.257\ NI$. Assuming that there is no magnetic leakage we can calculate the relation between lifting force and these quantities as follows:

The magnetic field of a solenoid has been shown to be $H = 1.257\ nI$ where n is the number of turns per centimeter length of the solenoid. In the above expression for magnetizing force N is the total number of turns. Then $n=\frac{N}{l}$ and $H=\frac{1.257\ NI}{l}$ That is, the field within a solenoid of N turns through which a current of I amperes is flowing is equal to 1.257 × ampere turns per unit length of magnetic circuit. From the relation, flux density = permeability × field strength, $B=\mu H$, we get

$$B=\frac{1.257\times NI\mu}{l}$$

Putting this value of B for B in the expression for the lifting force of the electromagnet we get

$$F(\text{dynes})=\frac{S(\text{sq. cm.})\ \dfrac{(1.257\ NI\mu)^2}{l^2(\text{cm.})}}{8\pi}$$

When S is in square inches, it must be multiplied by 6.452 to change it to square centimeters. Likewise, if l is in inches it

must be multiplied by 2.54 to change it to centimeters. But l is squared, and squaring 2.54 we get 6.452. The expression then becomes

$$F=\frac{6.452\times S\times\dfrac{(1.257\ NI\mu)^2}{6.452l^2}}{8\pi}$$
$$=\frac{S\times(1.257\ NI\mu)^2}{8\pi l^2}$$

To change this to pounds we must divide by 444,793 (nearly 445,000) and we thus finally get

$$F(\text{pounds})=\frac{S\times(1.257\times NI\mu)^2}{444{,}793\times 8\times\pi\times l^2}$$

or $$F=\frac{S\times N^2I^2\mu^2}{7075000\times l^2}$$

EXAMPLES

The lifting magnet, the contact area of which was given as 1.66 sq. in., is wound with 90 turns of wire, and the mean magnetic path is 5.12 in. How much can the magnet lift if it is magnetized by a current of 1.00 ampere and its permeability is 1610?

Solution.—

$S=1.66$ sq. in.
$N=90$ turns
$I=1.00$ ampere
$\mu=1610$
$l=5.12$ in.

Then $$F=\frac{1.66\times 90\times 90\times 1\times 1\times 1610\times 1610}{7075000\times 5.12\times 5.12}$$
$=188.0$ lb.

Since the permeability of a piece of iron is a variable quantity, the relation between lifting power and magnetizing current is not a straight line relation. This is seen readily from Fig. 48, the data for which were obtained by testing the small magnet already mentioned, and are given in the following table:

TABLE I

Current	Weight lifted
0.25	33.75
0.50	79.50
0.75	134.25
1.00	164.25

To facilitate computation a table is added which shows the relation between flux density and lifting force. The flux density is given in lines per square inch, and lifting force in pounds per square inch.

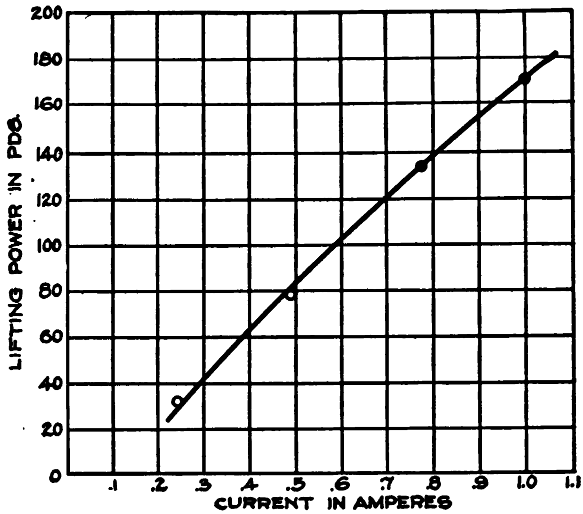

FIG. 48.

TABLE II

Lines per sq. in.	Pounds per sq. in.
6,450	0.577
12,900	2.308
19,350	5.190
25,800	9.228
32,250	14.39
38,700	20.75
45,150	28.26
51,600	36.95
58,050	46.72
64,500	57.68
70,950	69.77
77,400	83.07
83,850	97.47
90,300	113.1
96,750	129.7
103,200	147.7
109,650	166.6
116,100	186.8
122,550	208.1
129,000	230.8

The practical applications of electromagnets are too numerous to permit of listing them. A most important use is the magnetic field of all dynamoelectric machinery, one form of which is shown in Fig 49. This shows the electromagnets which develop the magnetic field of the direct-current generator.

Circuit breakers, the clutches of arc lamps, motor control

FIG. 49.

apparatus, the magnetic brake, magnetic ore separators, etc., are all operated by electromagnets.

RECAPITULATION

1. The *pull of an electromagnet* is given by

$$F=\frac{SB^2}{8\pi}\text{dynes}$$

where S = area of contact in square centimeters
B = flux density in lines per square centimeter

2. When the area of contact is given in square inches, and the flux, density in lines per square inch, the pull in pounds is

$$F=\frac{S\text{ (sq. in.)}\times B\text{ (per sq. in.) lb.}}{72126000}$$

3. When an electromagnet is excited by a current of I amperes flowing through N turns on an iron core of permeability μ and length of magnetic path l, the pull is

$$F=\frac{S\,(\text{sq. in.})\times N^2\times I^2\mu^2}{7075000\,l^2}\,\text{lb.}$$

CHAPTER IV

ELECTROMAGNETIC INDUCTION

62. Introduction.—In the preceding chapters we discussed the magnetism produced by an electric current when flowing through a coil of insulated wire. Some important applications of this principle were also briefly pointed out. If, however, magnetism could be produced only by a current from a battery, the industrial applications of electricity would be very limited. We could still use electricity for the operation of electric bells, the telegraph, telephones for short distances, and perhaps a few other minor uses. Electric lighting, electric railways, and allied applications would be practically unknown except as toys. It is the generation or development of electric current by means of the dynamo that has made possible the extended use of electricity in the distribution of power, production of light, electrolysis, transmission of intelligence, heating, etc.

Electromagnetic induction is the principle that whenever the number of magnetic lines linking a circuit is changed, an electrical pressure is developed within the conductor forming the circuit. The fundamental principles underlying the electromagnetic development of the electrical current will now be taken up.

63. Experiment 18. To Study Electromagnetic Induction.

Apparatus.—

Galvanoscope
Bar magnets
Horseshoe magnet
Solenoid
Dry cell
Wires

Operation.—This experiment is perhaps the most important that the student has been asked to perform so far, and it should therefore be repeated until all the principles that it illustrates are thoroughly understood.

First, determine the direction of the deflection of the compass needle when the current flows in at one terminal and out at the

other terminal of the galvanoscope coil. To do this place the compass under the 25-turn coil on the galvanoscope, and turn the galvanoscope so that the wire above the compass is parallel to the needle. Connect one dry cell to the binding posts of the 25-turn coil, and observe carefully the direction of the deflection of the *N* end of the compass needle. Determine at which binding post the current from the battery enters the galvanoscope by the rule given in Article 36. Observe to which binding post the carbon rod of the battery is connected. The current leaves the cell by this electrode and returns through the zinc cup. Make a note of this in order that you may determine the direction of the current flow from the deflection of the compass needle.

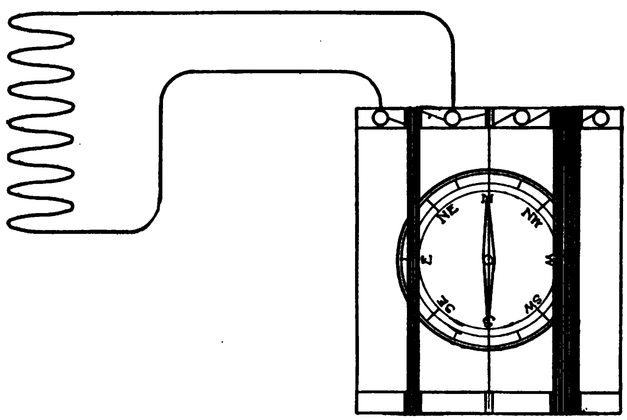

Fig. 51.

Next connect the solenoid to the 25-turn coil on the galvanoscope as indicated in Fig. 51. The wires connecting the solenoid and galvanoscope must be at least 4 ft. long so that the compass needle may not be influenced appreciably by the bar magnets to be used. Place the two bar magnets with their like poles together. Fasten them in this position by wrapping a string around them and tying it securely. Rubber bands may be used for this purpose.

Thrust one end of the bar magnets into the solenoid, observe and record the behavior of the compass needle. Does the needle move? If so, in which direction, east or west? What causes it to move? The magnets will have to be thrust into the solenoid quickly to cause appreciable motion.

On account of the crudeness of the apparatus the movement of the needle may be very slight. If the movement of the needle is imperceptible, connect a wire to the solenoid and make many more turns, or, better still, make a short coil of many turns, the more the better. Connect this in place of the solenoid and try the experiment. Although the deflection of the needle will not be great, it should be at least large enough to be noticed.

Quickly withdraw the bar magnets and observe the direction of the deflection of the needle. Repeat this until you are certain of the results.

From the direction of the deflection of the needle, determine the direction of the current in the solenoid and galvanoscope coil. Is the end of the solenoid of the same or of opposite polarity as the end of the magnet which was introduced? If you cannot tell at first, repeat the experiment until you are sure of your answer.

Reverse the bar magnets and repeat the experiment. In place of the bar magnets use the horseshoe magnet. Place one pole inside of the solenoid and withdraw it quickly. To prevent abrasion of the insulation on the solenoid coil, first wrap a sheet of writing paper around the solenoid and fasten it in place by a string or rubber band. Perhaps it will be impossible to move the horseshoe magnet into the solenoid quickly enough to cause a deflection. It can, however, be withdrawn with sufficient speed to cause a perceptible deflection.

Reverse the poles of the magnet and repeat. Compare the results obtained with the horseshoe magnet with the results obtained with the bar magnets. Prepare a table for your data thus:

TABLE III

Bar magnets	Deflection of N-pole of compass needle
N-pole moved into solenoid......	Toward east or west. Put in here the proper description.
N-pole withdrawn..............	Toward east or west. Put in here the proper description.
S-pole moved into solenoid.......	Toward east or west. Put in here the proper description.
S-pole withdrawn...............	Toward east or west. Put in here the proper description.

TABLE III—(*Continued*)

Bar magnets	Deflection of N-pole of compass needle
Horseshoe magnets	
N-pole inside of coils; magnet moved in.	Toward east or west. Put in here the proper description.
N-pole inside of coils; magnet moved out.	Toward east or west. Put in here the proper description.
S-pole inside of coils; magnet moved in.	Toward east or west. Put in here the proper description.
S-pole inside of coils; magnet moved out.	Toward east or west. Put in here the proper description.

64. Theory.—This experiment with the apparatus available will only illustrate principles, and even that not satisfactorily in every respect on account of the few turns on the solenoid and lack of sensitiveness of the galvanoscope. If a sensitive galvanometer were used in place of the galvanoscope, measurements could be made which would be very instructive.

In the experiments with the magnet and electromagnet the student learned that the space surrounding a magnet is permeated or filled with a magnetic influence, or perhaps it would be better to say that the space surrounding a bar magnet has some unique properties. These properties we call magnetic, and we also call the space that has these properties a magnetic field.

In the experiments with the electromagnet it was shown that a coil carrying an electric current has the same magnetic properties as a bar magnet; in short, that a current-bearing wire is surrounded by a magnetic influence and will magnetize an iron bar. An electric current produces a magnetic field. Conversely it is reasonable to expect that if a magnetic field be introduced into a coil, or if a magnetic field is built up around a wire, a current will be developed in the wire. The results of experiment 18 show this is precisely what happens. It is not the metal that causes the current in the solenoid, but the magnetic field surrounding the iron. The student can verify this by trying the experiment with an unmagnetized piece of steel and seeing if the needle is deflected.

In order that the student may have a clear understanding of the principles of the operation of electrical apparatus, he must

realize that the magnetic field surrounding a magnet is the seat of the property or energy that causes a current in the coil.

Furthermore, the results of the experiment show that when the *N*-pole of the bar magnet was thrust into the coil the deflection of the needle was in one direction, and when the magnet was withdrawn the deflection was in the opposite direction. While the bar magnet remained stationary the compass needle remained stationary. These facts show that the direction of the current is determined by the polarity of the magnet and the relative motion between the coil and the magnet.

Another important principle is the fact that the motion of the bar magnet is opposed by the induced current. By induced current is meant the current developed in the coil. Careful observation will show that when the *N*-pole of the magnet was thrust into the coil, the current in the galvanoscope circuit was in such a direction as to develop an *N*-pole at the end of the coil where the magnet enters. This developed *N*-pole opposes the introduction of the bar magnet. Again, when the magnet is withdrawn the deflection of the needle is in the opposite direction showing that the current has reversed. A careful inspection of the coil, and an application of the rule which gives the relation between the direction of current and the magnetic lines, will show that the end of the coil near the *N*-pole of the magnet is a south pole. This south pole attracts the magnet and again opposes its motion.

There is still another way of showing that the induced current opposes the motion of the bar magnet.

Every time the needle is deflected from its position of rest, some work must be done, or energy must be spent. This energy must be supplied by the operator who thrusts the magnet into the coil. But no energy can be transferred from one system to another unless the second system reacts upon the first. This is merely an extension of Newton's third law which is usually stated "action equals reaction, but is in opposite direction." A steam engine running idle does no work as there is no opposition to its motion. The moment a load is thrown on, it pushes against the engine just as much as the engine pushes against it, and work is done. Unless there is a reaction, the applied force can do no work. Since some energy must be transferred from the operator's hand to the needle to cause it to deflect, the induced current must react against, or oppose, the

motion of the magnet. A clear understanding of this principle will help the student to understand the principles of operation of electric machinery.

It has been pointed out already that the induced current flows only so long as there is relative motion between the magnet and the coil. When this motion ceases the current ceases. There is thus also a relation between the current induced and the speed with which the magnet is moved.

65. Law of Electromagnetic Induction.—Throughout the foregoing discussion reference has constantly been made to

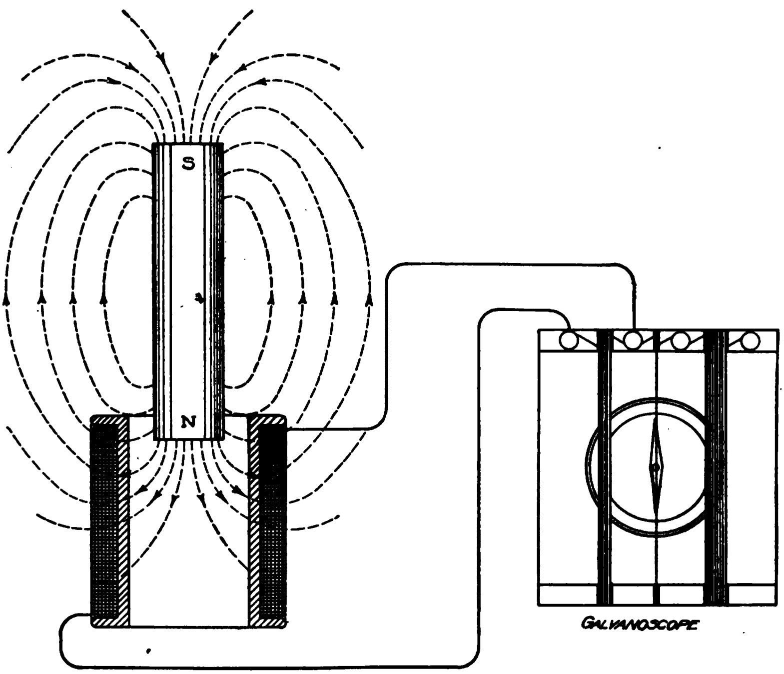

Fig. 52.

"induced current" as though that were the immediate result of introducing the bar magnet within the solenoid. This is because the presence of the current is more easily made apparent. The immediate result of the relative motion between a magnetic field and a coil is an electromotive force, which, when the circuit is closed, causes a current to flow. It is possible to express the value of this electromotive force (e.m.f.) in terms of the number

of turns on the coil, and the number of magnetic lines cut per second. This relation we will now develop.

Fig. 52 represents a section of a coil and a permanent bar magnet. The coil is shown connected to a current-detecting instrument. It will be observed that, as the magnet is moved into the coil, the turns or convolutions of the coil cut across the magnetic lines. Suppose the coil has only one turn; every time this turn cuts one magnetic line some electromotive force is induced or developed in the turn. In the experiment it was shown that the deflection of the compass needle varied with the speed with which the bar magnet was moved in and out of the coil. The induced electromotive force thus depends not only upon the total number of magnetic lines cut, but upon the number cut per second. Thus if the total number of lines cut by the coil of one turn in t seconds is Φ (pronounced phi) the number cut per second will be $\Phi \div t$, and accordingly the electromotive force induced in one turn will be determined by $\frac{\Phi}{t}$. If the same number of lines per second is cut by a second turn, an exactly equal e.m.f. will be induced in that turn, and as the two turns are connected so that the e.m.f. induced in one turn is added to that induced in the next turn, the total e.m.f. will be twice that induced in one turn. Exactly in the same way an equal e.m.f. will be added for every additional turn of the coil. The total e.m.f. will then be equal to the e.m.f. induced in one turn multiplied by the number of turns on the coil. Calling the total number of turns on the coil N, and the total e.m.f., E, we can represent this relation thus:

$$E = N\frac{\Phi}{t}$$

$$= \frac{\text{Number of turns} \times \text{number of magnetic lines}}{\text{Time, in seconds}}.$$

66. Unit of Induced E.M.F.—The unit of electromotive force may be defined in two ways. That is, its definition may be based on two different physical phenomena. According to one definition the practical unit of electromotive force is a certain fraction of the pressure of a standard cell. This will be explained later. The other physical phenomenon upon which the definition is based is the rate at which the magnetic lines are cut. Thus when one turn of a wire cuts one magnetic line per second an

e.m.f. of a definite value is induced. This value is called the absolute unit of electromotive force. For practical purposes this unit is too small. The *volt,* which is the practical unit, is equal to the pressure induced when one turn cuts 100,000,000 magnetic lines per second. This value, 100,000,000, is usually written 10^8, which means 10 multiplied by itself 8 times. Thus if it requires a cutting of 10^8 lines by one turn to develop one volt, the number of volts induced in a coil of N turns when it cuts Φ lines in t seconds is then

$$E(\text{volts}) = \frac{N\Phi}{t \times 10^8}$$

EXAMPLES

1. Suppose the number of magnetic lines in a coil increases from 0 to 800,000 in 0.02 of a second. How many volts are induced in a coil of ten turns?

Solution.—

$$N = 10$$
$$\Phi = 800{,}000$$
$$t = 0.02$$

Then

$$E(\text{volts}) = \frac{10 \times 800000}{0.02 \times 100000000}$$
$$= 4 \text{ volts}$$

2. The magnetic field of a generator has a coil of 2,000 turns; the circuit is suddenly broken so that the flux of 10,000,000 lines decreases to zero in 3/100 second. What voltage is induced in the coil?

Solution.—

$$N = 2{,}000$$
$$\Phi = 10{,}000{,}000$$
$$t = 0.03$$

Then

$$E(\text{volts}) = \frac{2000 \times 10000000}{0.03 \times 100000000}$$
$$= \frac{2000}{0.03} = 6666.7 \text{ volts}$$

67. The Development of an E.M.F. by Electromagnets.—In the preceding discussion the principle of electromagnetic induction was illustrated by the use of permanent bar magnets. It is not practical to make large electric-current generators by using permanent magnets. The most common use of permanent magnets for the induction of an e.m.f. is the magneto tele-

phone ringer, Fig. 17, and magneto-generators for gasoline engine ignition. Neither one of these requires a large current.

When large currents are to be generated, electromagnets are employed for supplying the magnetic field. The fundamental principles of inducing electric currents by the use of electromagnets will be made clear by the following experiment.

68. Experiment 19. Induction of E.M.F. by Electromagnets.

Apparatus.—

Electromagnet
Galvanoscope
Dry cells

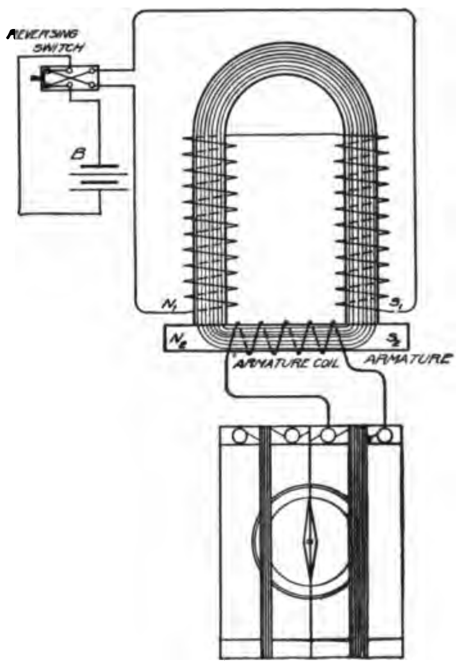

Fig. 53.

Operation.—First determine the relative direction of the flow of current through the galvanoscope coil and the direction of the deflection of the N-seeking end of the compass needle, in the same way as in experiment 18. Make a note of this.

Around the central portion of the rectangular armature of the electromagnet wind about 25 turns of annunciator wire. The ends of the armature must be left bare so that good contact can

be made with the electromagnet core. Place the armature up against the electromagnet, and connect the coil around the armature to the 25-turn coil on the galvanoscope as indicated in Fig. 53. To the electromagnet coil connect two dry cells in series through the reversing switch. This connection is diagrammed in Fig. 53. Close the switch and observe the behavior of the compass needle.

Determine the direction of the current flow in the electromagnet coil. Mark the N-pole of the electromagnet.

From the direction of deflection of the magnetic needle determine the direction of the current flow in the coil around the armature. This current also tends to magnetize the iron core. Mark the end of the core that would be a N-pole if the core were magnetized by this induced current. Does the induced current develop magnetism in the same or opposite direction as the electromagnet coil?

Open the battery circuit suddenly and compare the resulting deflection with that when the circuit is closed. Determine the direction of the induced current in the galvanoscope coil when the circuit is broken. Is this direction the same as when the circuit is closed? Does the induced current aid or oppose the magnetizing effect of the electromagnet coil?

Close the switch in the opposite direction (this reverses the battery connection) and repeat the experiment. How is the current in the solenoid developed? Study carefully all of the conditions, and repeat the experiment until all of the principles are understood.

69. Theory.—The foregoing experiment illustrates another most important and fundamental principle. The principle has wide application, and, if any principle can be considered more important than any other, the principle exemplified by this experiment is perhaps the most important in the realm of electromagnetism. The similarity between the process of inducing currents by electromagnets and permanent magnets must be evident to the student.

In connection with experiment 18 we learned that when a magnetic field is moved relatively to a coil of wire, in such a way that the turns of the coil cut across the magnetic lines, an e.m.f. is induced. In that case either the coil or magnet is held stationary while the other is moved. The necessity for this lies in the permanent attachment of the magnetic field to the

steel bar. It must be evident also that the necessary condition for the development of an e.m.f. is not relative motion between the coil of wire and the iron bar, but between the coil and the magnetic field. If by any means the relative positions of the coil and field are varied, or if a magnetic field is either built up within or caused to drop out of the coil, in general, an e.m.f. is induced. Previous experiments have shown that when an electric current is passed through a coil surrounding an iron core, the iron is strongly magnetized; that is, the current builds up a magnetic field. The iron core of the electromagnet is magnetized in this way. The magnetic lines form closed curves and thus pass through the iron armature and its coil. This is indicated in Fig. 53. The building up of the magnetic lines within the armature of the electromagnet produces the same result as the introduction of a permanent magnet. Thus by the mere building up of a magnetic field within the core of a coil an e.m.f. is induced, just as when a permanent magnet is introduced.

Any change or variation in the current in the electromagnet coil will produce a like change in the number of magnetic lines that thread through the armature coil, and consequently any variation in the current will induce an e.m.f. If the armature coil is closed, the induced e.m.f. will force a current through this circuit in such a direction as to oppose the building up of the magnetism produced by the electromagnet coil. Thus in Fig. 53, if the electromagnet core has the polarity indicated, the induced current will tend to cause poles of like kind on the armature; that is, if the pole due to the current in the electromagnet coil is plus or N, the pole that the induced current tends to produce adjacent to the N pole of the electromagnet core is also a N-pole. This is indicated in the figure by N_1, N_2, and S_1, S_2. This is exactly what one should expect from the principles of action and reaction explained in preceding paragraphs. This law that the induced e.m.f. is always in such a direction that it opposes the action which induces it is known as Lenz's law, and is evidently a particular case of the general law of action and reaction.

70. Relation between Primary Current and Induced E.M.F.—That some definite relation exists between the magnetizing current and induced e.m.f. must be evident; for, by the law of conservation of energy, one cannot get more energy out of any transforming device than is put into it. The energy in our experiment is put into the electromagnet coil—which hereafter we shall call

the "primary." This energy is transformed by means of the magnetic field and solenoid into the energy of an electric current within the coil on the armature, which we shall hereafter call the "secondary." The problem to solve is to determine the relation between the current in the primary and e.m.f. induced in the secondary coil.

In the discussion on electromagnetism it was shown that when a current of I amperes flows through a coil of N_1 turns surrounding an iron core, the number of magnetic lines developed is given by:

$$\Phi = \frac{1.257\ N_1 I \mu A}{l}$$

where

Φ = total number of magnetic lines
N = total number of turns on primary coil
μ = permeability of magnetic circuit
A = cross-sectional area of primary coil core in square centimeters
l = total length of magnetic circuit in centimeters

It has also been shown that the total e.m.f. induced in a coil, all of whose turns cut across a magnetic field, is given by

$$E\,(\text{volts}) = \frac{N_2 \Phi}{t \times 10^8}$$

where N_2 is the total number of turns in the secondary winding. If all the magnetic lines produced by the primary current pass through the secondary coil, Φ will be the total number of magnetic lines cut in time t. This total flux is equal to

$$\Phi = \frac{1.257\ N_1 I \mu A}{l}$$

Putting this value of Φ in the equation above we get

$$E\,(\text{volts}) = N_2 \frac{1.257\ N_1 I \mu A}{10^8\ l \times t} = \frac{1.257\ N_1 N_2 I \mu A}{10^8\ l \times t}$$

This equation, translated into words, means that the voltage induced in the secondary, Fig. 53, is equal to 1.257 times the product obtained by multiplying together the primary and secondary turns, the current, permeability and cross-sectional area of the

magnetic circuit, and this product divided by 10^8 times the length of the magnetic circuit, by the time required to build up the magnetic field. This expression also shows that for a given value of the primary ampere turns, the voltage induced in the secondary varies with the number of secondary turns.

We have purposely omitted any reference to the value of the induced current, for this value depends upon some other quantities which will be explained later.

EXAMPLES

1. A coarse wire of 500 turns is wound around an iron ring whose cross-sectional area is 10 sq. cm. and mean length 60 cm. On the outside of this primary coil is wound a secondary coil of 1,000 turns. What voltage will be induced in the secondary coil if the current in the primary changes from 0 to 5 amperes in 0.1 second? Assume the permeability to be 500.

Solution.—

Primary turns $N_1 = 500$
Secondary turns $N_2 = 1{,}000$
Current $I = 5$ amperes
Permeability $\mu = 500$
Cross-section $A = 10$ sq. cm.
Length of magnetic circuit $l = 60$ cm.
Time, $t = 0.1$ sec.

Then

$$E = \frac{1.257 \times 500 \times 1000 \times 5 \times 500 \times 10}{10^8 \times 60 \times 0.1}$$
$$= 26.2 \text{ volts}$$

2. What voltage will be induced in the secondary coil mentioned in example 1, if, when the current is 7 amperes, the circuit is broken and the current drops to zero in 0.01 second?

Solution.—

$I = 7$ amperes
$t = 0.01$ sec.
Other quantities same as in example 1.

Then

$$E = \frac{1.257 \times 500 \times 1000 \times 7 \times 500 \times 10}{10^8 \times 0.01 \times 60}$$
$$= 366.7 \text{ volts}$$

These two examples show also that the induced voltage depends not alone upon the primary current and number of secondary turns, but also upon the time required for the magnetism to be built up or to decay.

71. Practical Applications.—This principle of inducing an e.m.f. by means of electric currents has so many applications that it will be possible to explain and illustrate only a few.

One of the oldest pieces of apparatus that operates in accordance with the foregoing principles is shown in the diagram of Fig. 54 and is known as an induction coil. The essential features of the induction coil are nearly the same as those of the electric bell already studied, with the exception that a second coil of many turns of fine wire is wound around the electromagnet core. Thus in Fig. 54 the iron core *N–S* is shown as being wound with two coils of wire, one heavy and the other light. The heavy or primary winding is connected to a battery *B*, vibrator *A*, and screw *C*. As shown in the figure, another circuit which contains a condenser is connected to *A* and *C*.

When the primary circuit is closed the current from the battery magnetizes the iron core and the resulting development of mag-

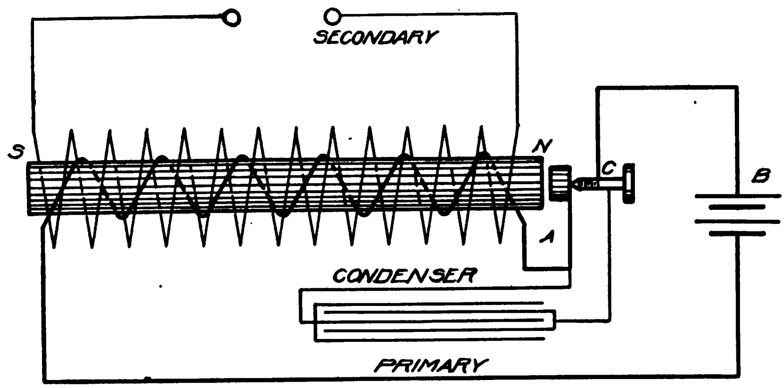

Fig. 54.

netism through the secondary coil induces an e.m.f. This e.m.f. is, however, not very large, as the current increases with comparative slowness for reasons that will later be explained. When the magnetism of the core has reached a sufficiently high value so that the attraction of the core for the vibrator *A*, which is made of soft iron, is greater than the pull on the spring *S*, the circuit is broken at *C* just as in the electric bell. As soon as the primary circuit is broken the iron core loses most of its magnetism and a much higher e.m.f. is induced in the secondary. As it has been shown that the induced e.m.f. depends upon the number of turns on the secondary and the time required to magnetize or demagnetize the iron core, it is clear that the greater the number of breaks per second of the primary current at *C* the greater will be

the induced e.m.f. Without going into details, it may be worth while to state that the purpose of the condenser is to prevent excessive sparking at the contact point C; and because it discharges through the primary in an opposite direction to that of the current a greater degree of demagnetization is obtained.

The current through the primary is furnished by a few cells of low voltage, while the voltage induced is comparatively very high, as it depends upon the number of turns on the secondary and the rapidity of breaking the circuit. The induction coil has many different forms and is used very extensively. In the form shown in Fig. 54 it is used for gas and gasoline engine ignition, for wireless telegraphy, and X-ray work.

In a modified form it is used in telephones. Fig. 55 shows a telephone circuit in which two induction coils are shown. As is evident from the diagram the telephone circuit consists of three separate circuits. There is a local circuit at each station consist-

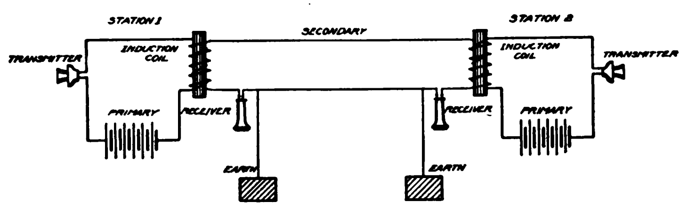

Fig. 55.

ing of the battery, transmitter, and primary of the induction coil. The other circuit is composed of the two receivers and the two secondary circuits of the induction coils.

As has just been shown, any variation in the primary circuit current induces an e.m.f. in the secondaries. This induced e.m.f. is of much higher voltage than the voltage of the primary circuit and hence will be more effective over a longer distance. The induction coil used in telephone work has no vibrator for the reason that the primary current is caused to increase and decrease in value by the vibrations of the diaphragm of the transmitter.

The use of an induction coil in wireless telegraphy is shown in Fig. 56. This, of course, is a diagram of the simplest form of wireless apparatus. For commercial purposes the apparatus is much more complicated, although the fundamental principles are the same.

The apparatus at the sending station consists of an ordinary

induction coil T_1, a condenser of variable capacity C_1, and a second induction coil T_2 which is also adjustable. Between the condenser C_1 and the induction coil T_2 is a spark gap s. The current for operating the induction coil T_1 is supplied by an alternating current generator through a key K. The secondary of the induction coil T_1 charges the condenser C_1 until its pressure rises high enough to cause a spark to jump across the air gap s. This discharge of the condenser is oscillatory and of very high frequency. These oscillations in the condenser circuit induce like oscillations in the secondary of the induction coil T_2 and the aerial line.

The receiving apparatus is much like the sending apparatus, with the exception that the air gap is omitted from the condenser circuit, and a condenser, a telephone receiver and a crystal of carborundum replace the generator A.

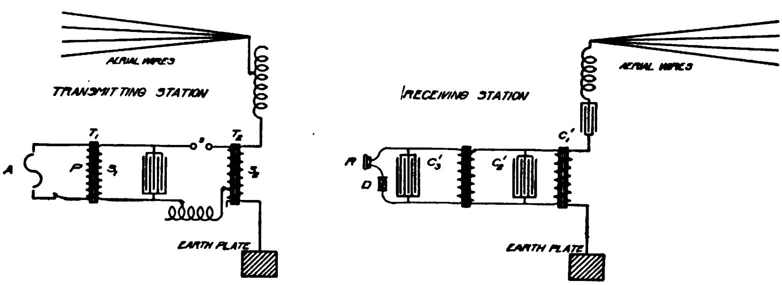

FIG. 56.

The waves sent out by the sending apparatus induce oscillations in the receiving apparatus with which the sending apparatus is tuned. These oscillations induce other oscillations in the condenser circuits, C_1', C_2' and C_3'. The detector of the oscillations in the circuit C_3' is merely a crystal of carborundum which has the property of permitting the current to flow in one direction only. The use of three adjustible circuits C_1', C_2' and C_3' permits the picking up of oscillations of a given frequency only. For non-selective receiving the circuit C_3' is omitted and the telephone receiver is connected directly across the condenser C_2'. The student will observe that in wireless telegraphy induction coils are used in connection with condensers. This is for the purpose of getting an oscillatory charge and discharge of high frequency. This is not intended as a complete exposition of wireless teleg-

raphy, but merely an exemplification of the use of induction coils in wireless transmission of messages. The sending apparatus in the Arlington Station is shown in Fig. 57.

72. Self Induction.—The fundamental principle of self induction is the fact that whenever there is relative motion between a conductor and a magnetic field in such a way that the wire cuts across the magnetic lines, an electromotive force is induced in the conductor. It evidently makes no difference what may be the source of the magnetic field. It may be due to a permanent magnet, or to an electric current.

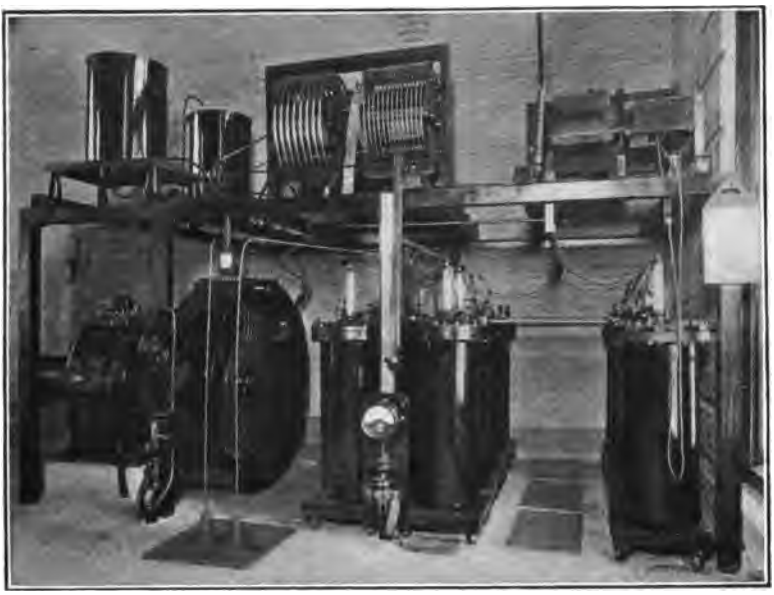

Fig. 57.

The manner in which a current in one coil induces or develops an e.m.f. in another adjacent coil has just been explained. The magnetic field produced by a current in a coil links with or penetrates the coil itself, as shown in Fig. 30. The cutting of the turns of the coil by these magnetic lines induces an electromotive force in exactly the same way as when the magnetic field is due to another adjacent coil. There is this difference, however, when a current in one coil induces an e.m.f. in an adjacent coil, the induced current can be made apparent by closing

the circuit of the second coil, when a current will flow which can be detected. The presence of an induced e.m.f. in the first, or primary, coil cannot be made apparent in this simple manner, at least not while the primary current is increasing. It has been shown that the e.m.f. induced in a secondary coil opposes the action of the current in the primary coil. This is also true of the e.m.f. induced within the primary coil itself.

In describing the induction coil it was pointed out that the purpose of the condenser was to prevent sparking at the point where the primary circuit is broken. This sparking does not take place when the circuit is closed but when the circuit is opened, as can be shown readily by experiment. For this experiment the electric bell can be used in place of the induction coil.

73. Experiment 20. To Study the Cause of Sparking at Break in Circuit of an Electric Bell.

Apparatus.—
Electric bell
Three dry cells

Operation.—Connect the three dry cells and electric bell in series. Take hold of the clapper and let it make contact with the screw and observe carefully that no spark appears when the contact is made. Break the circuit quickly; that is, let the clapper swing against the bell, and note carefully the appearance of the spark at the point of the screw. Repeat this experiment until you are certain that the spark appears when the circuit is broken and not when it is closed. Can you explain the cause of the spark?

74. Theory.—When the circuit is closed the current builds up the magnetic field, which in turn induces an e.m.f. This induced e.m.f. opposes the sudden rise of current, hence no spark is caused at the point of contact. When the circuit is broken, the applied e.m.f. is no longer effective in causing a current, and the magnetic field decays or disappears. This disappearance of the magnetic field is also effective in producing an e.m.f., but the e.m.f. induced tends to cause a current in the same direction as the primary current. The rapidity with which the magnetic field disappears and the number of turns of the electromagnet develop an e.m.f. large enough to cause a spark to jump across the contact points. This spark is due to the electromotive force of self induction which opposes the rise of current when the circuit is closed, and tends to keep the current flowing when the

circuit is broken. This subject of self induction is so important that we are justified in looking at it from still another viewpoint.

By this time the student should realize fully that an electric wire is surrounded by a magnetic field, and that this field is built up as the current increases; remains constant while the current remains constant; and decays with the decrease of the current.

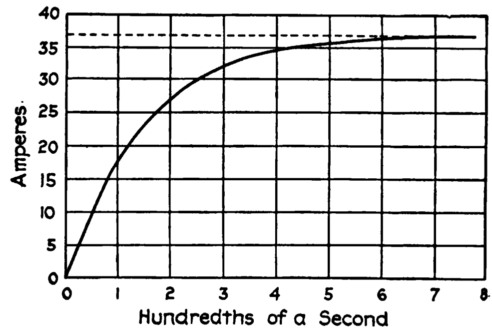

Fig. 59.

The building up of the magnetic field requires energy which must be supplied by the current. It is a fundamental principle in mechanics that no energy can be transferred to or stored in any mechanism, machine or system, unless that mechanism, machine or system, reacts upon the system from which the energy is to

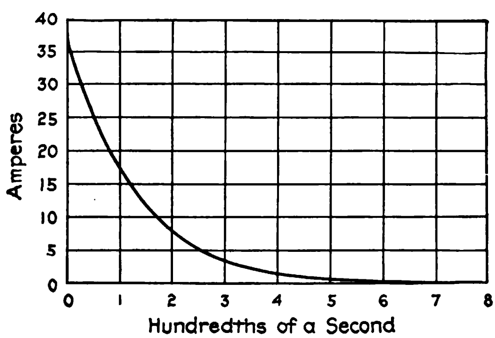

Fig. 60.

be taken. There can be no action unless there be something to act upon which will, in its turn, react. Illustrations of this law are numerous. For instance, when powder explodes in a cannon, some of the energy set free by the explosion is transferred to the cannon ball. If the cannon ball did not tend to prevent

or confine the explosion, no energy would be stored in it. Again, when the cannon ball strikes a wall, the energy of the ball is transferred to the brick or stones which impede its progress. The air through which the ball passes gets relatively little of the energy as it offers comparatively little resistance to the motion of the ball.

Since it requires energy to build up a magnetic field, or, in other words, since the magnetic field is a seat of energy, the magnetic field must react against the current producing it. This reaction is made apparent by the retardation in the growth of the current. The stronger the magnetic field, or the greater the number of turns of wire on the coil, the more slowly will the current increase. Fig. 59 is a curve showing the growth of a current in a coil that has considerable self inductance. The greatest current that can flow in the circuit is 36.67 amperes, but the current does not reach this value until 0.8 second after the closing of the circuit. At the end of 0.1 second the current is only about 17.5 amperes. When the circuit is opened the current does not immediately drop to zero, but decreases gradually, as shown in Fig. 60.

75. Analogies.—The effect of self induction in preventing the sudden increase or decrease of a current may be considered as analogous to the action of the inertia of a flywheel of an engine. When the steam is first admitted to the cylinder, the speed of the flywheel increases gradually. Even if the throttle or steam pipe were fully opened, the speed of the flywheel would not suddenly jump from stand-still to full speed.

While the speed of the flywheel is increasing, the flywheel is pushing against the pressure of the steam, and the energy of the steam is being transferred to the flywheel. Only by reacting against the steam pressure can this energy be transferred. This reaction prevents a sudden increase in the speed.

When the flywheel has acquired full speed, and the speed has become constant, a pressure only sufficient to overcome friction is necessary, and no more energy is being absorbed or taken up by the wheel.

If the steam be shut off suddenly, the engine will not come to a sudden stop, but the energy that has been stored in the flywheel will keep it running in the same direction for some time. The motion will continue until all of the energy stored in the flywheel has been returned to the driving mechanism of the engine and dissipated as heat.

76. Self Inductance.—The properties of the coil that cause an electromotive force to be induced in it when a current increases or decreases is called *self inductance.* This property depends upon the number of turns on the coil and the presence of iron within the circuit. The value of this property when a change of 1 ampere per second induces 1 volt in the circuit, is the unit of self inductance and is called the *henry.* This value of the self inductance of a coil in terms of the number of turns and permeability of the magnetic circuit, can be calculated readily. We showed that when a current of I amperes flows through a coil of N turns, if the coil is a long solenoid, the field strength within the solenoid is given by

$$H = \frac{1.257 \times NI}{l}$$

If the coil has an iron core of cross-sectional area A and permeability μ, the total number of magnetic lines is given by

$$\Phi = \frac{1.257 NI\mu A}{l}$$

We have also shown that when a magnetic field is built up within a coil, the electromotive force induced is proportional to the rate at which the field is built up, usually expressed as the rate at which the magnetic lines are cut by the turns of the coil. The coil is assumed to have N turns, and if the field is built up in t seconds, the voltage induced will be

$$\begin{aligned} E(\text{volts}) &= \frac{N\Phi}{10^8 \times t} = N \times \frac{1.257\, NI\mu A}{t \times 10^8 \times l} \\ &= \frac{1.257 N^2 \mu A I}{10^8 \times t \times l} \end{aligned}$$

For any given coil the quantity $\frac{1.257 N^2 \mu A}{10^8}$ is approximately constant and is the value of E in volts when I, the current, is 1 ampere, and t, the time required for the current to change 1 ampere, is 1 second. This constant value $\frac{1.257 N^2 \mu A}{10^8 l}$ is usually represented by the letter L. Thus

$$L = \frac{1.257 N^2 \mu A}{10^8 l} \text{ henrys}$$

and is called the inductance of the coil. It must be noted that this quantity depends solely upon the physical properties of

the coil, and not upon the current flowing in the coil. The e.m.f. induced, or the e.m.f. of self induction, depends not only upon the value of the inductance of the coil, but also upon the rate at which the current in the coil is changing; that is, upon $\frac{I}{t}$. Representing the value of self inductance by L we may write the expression for the induced pressure by $E=L\times\frac{I_1-I_2}{t}$. In this expression I_1 expresses the current at the beginning and I_2 the current at the end of some interval of time, and t represents the time during which the current changes from I_1 to I_2.

The value of L calculated in accordance with the expression

$$L=\frac{1.257N^2\mu A}{10^8 l}$$

is true only for very long solenoids or for coils wound upon an iron core which forms a complete magnetic circuit. It may, however, be used to obtain the approximate value of the inductance of shorter sloenoids.

EXAMPLES

1. A solenoid 100 cm. long, 12.567 sq. cm. in cross-section, without iron, is wound with 2,620 turns. What is its inductance?

Solution.—Since the solenoid has no iron core μ, the permeability is 1.

Then $L=\frac{1.257N^2A}{10^8 l}$

$N=2{,}620$

$A=12.567$ sq. cm.

$l=100$ cm.

and $L=\frac{1.257\times2620\times2620\times12.567}{10^8\times100}$

$=0.01$ henry

2. A coil of 2,000 turns is wound upon a cast-rion ring whose cross-section is 5 sq. cm. and mean length 40 cm. If the permeability of the ring is 1,250 what is the inductance of the coil?

Solution.—

$L=\frac{1.257N^2\mu A}{10^8 l}$

$N=2{,}000$

$A=5$ sq. cm.

$\mu=1{,}250$

$l=40$ cm.

Then $L=\frac{1.257\times2000\times2000\times5\times1250}{10^8\times40}$

$=7.85$ henrys

3. What will be the electromotive force of self induction in example 2, if the current changes from 0 to 5 amperes in 1/10 second?

Solution.—It was shown that the e.m.f. of self induction is equal to the inductance times the rate of change of current. The inductance of the coil in example 2 is 7.85 henrys, and if the current changes from 0 to 5 amperes in 1/10 second it is changing at the rate of 50 amperes per second; hence,

$$E = 7.85 \times 50 = 392.5 \text{ volts}$$

or, according to formula,

$$L = 7\ 85$$
$$I_1 = 0$$
$$I_2 = 5$$
$$t = 1/10 \text{ sec.}$$

Then $E = L\dfrac{I_1 - I_2}{t}$

$$= 7.85 \times \frac{0-5}{0.1}$$
$$= \frac{1.57 \times (-5)}{0.1} = -392.5 \text{ volts}$$

The negative sign merely shows that the induced pressure opposes the flow of current.

77. Practical Applications.—Self induction does not play a very prominent part in direct-current circuits, as it acts only while the current is changing. The time required for the effects of self induction to disappear in direct-current circuits is also, as a rule, very brief; hence in calculating direct-current circuits self induction usually is neglected.

In breaking the field circuit of a dynamo the effect of self induction may sometimes have a serious result. If the current is broken suddenly the e.m.f. of self induction may reach a very high value, and if the insulation is weak, it may be punctured and a short circuit result. It is thus advisable to have the field circuit closed through a relatively high resistance thus permitting the discharge of the field without damage. When lifting magnets, similar to the one shown in Fig. 44, were first used, the circuit was closed and opened by an ordinary double-pole switch. The inductive arc burned away the contacts very rapidly. It is now customary to provide a discharge resistance which is connected to the electromagnet coil by a switch of special design, when the circuit is opened.

RECAPITULATION

1. *Electromagnetic induction* is the principle of developing an electromotive force whenever the number of magnetic lines linking a circuit is changed.
2 The *electromotive force* induced in a conductor when it cuts across a magnetic field is proportional to the number of magnetic lines cut per second.
3. The *electromotive force* induced in a coil of N turns when a flux of Φ lines is changed in it in t seconds is given by $E=N\frac{\Phi}{t}$.
4. The *practical unit of electromotive force* is the *volt* and is the electromotive force induced in a conductor when it cuts 100,000,000 which $=10^8$ magnetic lines per second.
5. The *approximate value* of the electromotive force induced in the secondary of an induction coil is given by

$$E = \frac{1.257\, N_1 N_2 I \mu A}{10^8\, lt} \text{ volts}$$

where N_1 = primary turns
N_2 = secondary turns
I = change in current in t seconds
μ = permeability
A = cross-sectional area of magnetic circuit.

6. *Self induction* is the principle of developing an electromotive force within a conductor by the current within the same conductor.
7. *Mutual induction* is the principle of developing an electromotive force in a conductor when a current varies in an adjacent conductor.
8. *Self inductance* is the property of a coil which determines the value of the electromotive force of self induction when the current changes at the rate of 1 ampere per second.
9. The *unit of inductance* is the *henry*, usually symbolized by the letter L, and is defined as that inductance which develops an electromotive force of 1 volt when the current changes at the rate of 1 ampere per second.
10. Owing to the property of inductance, a current does not instantly rise to its maximum value in a coil, nor when the circuit is broken does it instantly drop to zero.
11. The approximate value of the inductance of a coil is given by

$$L=\frac{1.257\, N^2 \mu A}{10^8\, l}$$

CHAPTER V

CURRENT ELECTRICITY

78. Introduction.—The method of developing an electric current by electromagnetic induction has been briefly discussed and experimentally illustrated. For operations that require comparatively large currents, the electromagnetic process of current generation is usually used either directly, or indirectly by first charging a storage battery, and then using this as the source of current. The simple primary cell will serve, however, to furnish an electric current whose properties we shall now study. At the same time we are going to determine some of the main and most obvious characteristics of the simple cell.

79. Experiment 21. The Simple Voltaic Cell.

Apparatus.—

Strip of zinc
Strip of copper
Dilute sulphuric acid
Tumbler
A small quantity of mercury
Connectors and holder

Operation.—Procure about 1 oz. of pure sulphuric acid at a drug store and dilute this with water. The necessary degree of dilution is obtained by pouring one part of the acid into twenty parts of water. Rain water will be the best. Always pour the acid into the water; never the water into the acid. Be careful not to get any of the pure or dilute acid upon the hands or clothes; also never leave it in the tumbler where some one may accidentally drink it.

Take a strip of zinc and place it in a tumbler of dilute sulphuric acid. After a short time it will be observed that bubbles of gas are produced at the surface of the zinc and rise to the surface of the liquid. These are hydrogen bubbles and are due to the action of the acid upon the zinc. The acid combines with the zinc, producing zinc sulphate and giving off hydrogen.

After the zinc has been in the acid for a short time take it out

and with an old tooth brush or cloth rub some mercury over both sides of the zinc. Take only a small drop of mercury for this. When you rub the mercury on the zinc lay the zinc on a flat surface. Notice that mercury combines with the zinc, producing a bright surface. Coating zinc with mercury is called *amalgamation.*

Put the amalgamated strip of zinc into the dilute acid and again observe the action. Does the acid attack the zinc as readily as before?

Replace the zinc by a strip of copper and observe the action of the acid. Do you see any bubbles collecting on the copper and rising to the surface?

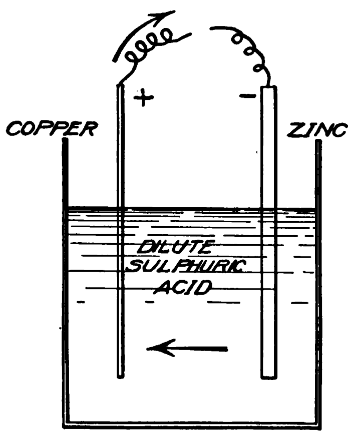

FIG. 61.

Next fasten the zinc and copper strips into the holder and dip both into the dilute acid as shown in Fig. 61. Connect a wire about 1 ft. long to one binding post. Touch the other binding post with the other end of the wire and notice whether bubbles arise. Connect the loose end of the wire to the other binding post and observe the action in the cell.

From which electrode do most of the bubbles arise? Disconnect the wire from one binding post and notice if bubbles continue to rise. Connect the wires. Do bubbles rise?

80. Theory.—The student has observed that sulphuric acid attacks the unamalgamated zinc, but that when the zinc is amalgamated the chemical action almost entirely ceases. The copper is not attacked by the acid to an appreciable extent. When the zinc strip alone is in the acid the energy liberated by the chemical action is all converted into heat. If the strip had been left in the acid for some time the electrolyte would have rapidly increased in temperature. Amalgamation almost entirely eliminated the chemical action.

The cause of the appearance of the hydrogen bubbles at the surface of the unamalgamated zinc when dipped into dilute sulphuric acid is that weak electrical currents are set up between the

zinc and the impurities in it—carbon or iron particles. If the zinc is pure these local currents cannot be set up, and consequently no hydrogen bubbles appear. Amalgamating the zinc stops this so-called *local action*, because the mercury coats the impurities while it dissolves the zinc. It is important, therefore, to amalgamate the zinc to prevent its wasting away while the cell is on open circuit. The zinc is under all circumstances consumed when the current is flowing. Amalgamation serves only to preserve the zinc when the circuit is open.

When both the zinc and copper strips are immersed in the acid and the outside terminals of the electrodes are joined by a copper wire, the chemica action again takes place. Hydrogen bubbles rise from the copper plate and the bubbles of another gas rise from the zinc electrode. If a thermometer is placed in the electrolyte it will be observed that the temperature rises much more slowly than when the unamalgamated zinc alone is used. The energy of chemical action is no longer being converted into heat, as previously, but when the proper test is made it will be found that an electric current is flowing. Some of the chemical energy is converted into electrical energy, which is again converted into heat in the electrodes, wire, and electrolyte.

81. Definitions.—A *voltaic cell* is the combination of electrolyte, electrodes, and container. More than one cell connected together is called a battery.

A *conductor* is any material along which a current of electricity will flow. The connecting wire used in the foregoing experiment is a conductor. All conductors are however not metallic; for instance the dilute acid is also a conductor. Conductors may thus be either solid or liquid. The conduction is, however, not the same in the two cases. Solid conductors as a rule transfer electricity without undergoing any change or decomposition. Liquids as a rule are decomposed, when a current of electricity is passed through them. This is not true in every case, as for instance in mercury.

82. Volt-ammeter.—The student will hereafter use the instrument shown in Fig. 62 in place of the galvanoscope for detecting an electric current. This instrument is a combined voltmeter and ammeter and hence is called a volt-ammeter. The general principle of operation of this instrument is readily understood. The deflection is produced by the interaction of the magnetic

field produced by the electric current flowing through a coil of fine wire mounted so as to rotate in the air gap of a permanent magnet, and the magnetic field due to this permanent magnet. Both the coil and magnet poles are visible through the window in the cover of the instrument. The instrument is thus in principle much the same as the galvanoscope with this difference. On the galvanoscope the coil is fixed and the compass needle, which is a permanent magnet, is forced to turn by the action of the magnetic field due to the coil. The deflection of the needle is indicated in degrees.

FIG. 62.

In the volt-ammeter the permanent magnet is fixed and the coil is mounted on a spindle so that it can rotate, its motion being controlled by a coiled spring. The graduations of the scale are in volts and amperes instead of degrees. These differences make the instrument more sensitive, accurate, and convenient.

Since this is the first time that the student is asked to use a delicate instrument, some instruction for its use will be given. First examine the volt-ammeter and observe that it has 3 binding posts, one marked +, the one next to it marked A, and the third marked V. In connecting this instrument to a circuit always

connect the + post to the wire that is connected to the carbon, copper, or positive terminal of the cell or other source of e.m.f. *Never* connect the post *A* to the zinc terminal of a cell unless some resistance is included in the circuit. If you should connect a dry cell directly to posts + and *A*, the current through the instrument may be too large and the instrument may be damaged. While one cell alone may not cause serious trouble, more than one undoubtedly will cause damage. *Never* connect this instrument to a house-lighting circuit. The meter is not designed for such use, and if so connected it will undoubtly be burned out. Follow the instructions carefully and you will have no trouble.

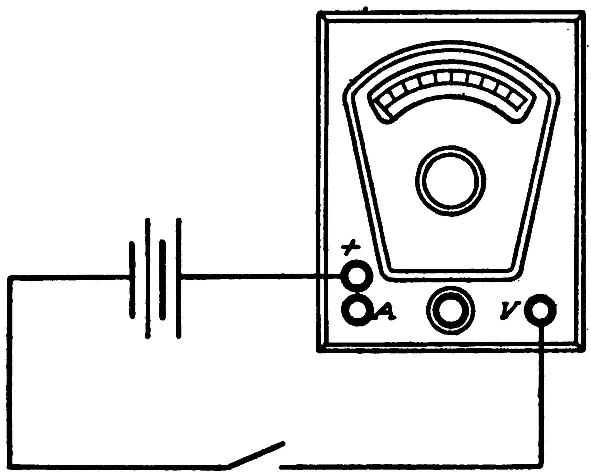

Fig. 63.

83. Experiment 22. Electromotive Force or Pressure.

Apparatus.—

Volt-ammeter
Simple voltaic cell
Dry cell

Operation.—Connect the positive terminal of the simple voltaic cell to the + binding post of the volt-ammeter by means of a short piece of copper wire. Connect the other cell electrode to the binding post marked *V*. When the connections are made as indicated in Fig. 63, observe and record the deflection. What causes the pointer to move?

Disconnect the voltaic cell and connect one dry cell to the volt-

ammeter in the same way, and again observe and record the deflection.

84. Theory.—The student learns from the foregoing experiment that different cells cause different deflections of the voltmeter. The cause of the deflection is a current of electricity which flows through the movable coil of the voltmeter. Naturally the student will ask, what causes the current to flow? This question is more easily answered by analogy than directly.

Experience shows that water flows through pipes from points of higher to points of lower mechanical pressure, and to raise water through a pipe requires pressure. By analogy we say that

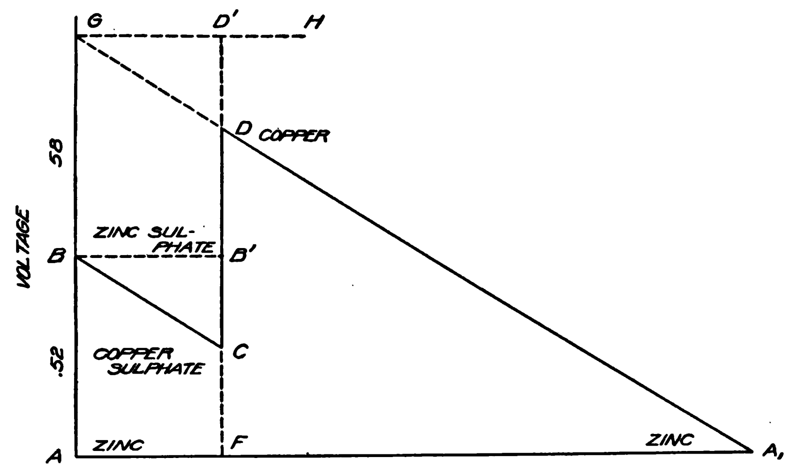

Fig. 64a.

electricity is transferred from points of higher to points of lower electrical pressure. The action in a cell may be considered analogous to the action of a pump in a water circuit. At the zinc electrode the pressure rises, forcing the electricity toward the copper through the electrolyte. At the copper electrode there is another increase in pressure so that the copper electrode is at the highest electrical pressure in the circuit. This is represented in the diagram of Fig. 64a. This is a diagram which attempts to represent the action in the cell. Between the zinc plate and the acid solution there is a sudden rise in pressure of 0.52 unit, so that the pressure of the zinc sulphate solution next the zinc plate is represented by the point B. Then follows a drop in pressure through

the cell until the copper electrode is reached, when another rise of pressure occurs. This rise is about 0.58 unit. The pressures at the copper sulphate and copper electrode are represented by points C and D respectively. From the copper plate the pressure falls off uniformly along the external circuit, until the zinc plate is again reached. To complete the analogy, the figure should be considered as wound upon the surface of a cylinder so as to make A_1 coincide with A. This is shown in Fig. 64b. The cause of the flow of electric current is called electromotive force, or in practice pressure or voltage. This pressure is in some way due to the chemical action in a cell. In a generator it is produced in another way as will be shown.

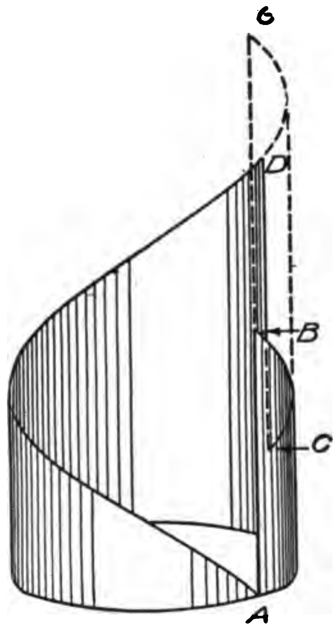

FIG. 64b.

The absolute value of the pressure developed in a cell depends upon the material of which the cell is made. This is shown by the fact that the voltmeter deflection is less when the simple voltaic cell is connected than with the dry cell. Other illustrations of this will be given later.

The student must not confuse pressure with current. The current that a given cell will give depends upon several things, but the pressure or electromotive force is determined by the materials of which the cell is made. Many different substances can be used for this purpose, but in every case the action of the electrolyte must be greater on one substance than on the other. For the negative electrode zinc is almost invariably used in commercial voltaic cells.

Volt.—The unit of electrical pressure is called the volt. Numerically it is about equal to the pressure of the simple voltaic cell, when fresh, with copper and zinc as electrodes and dilute sulphuric acid for the electrolyte. It is defined as $\frac{100000}{101830}$ of the pressure of a Weston standard cell. This is a voltaic cell made according to certain definite specifications from materials of known degrees of purity. Electrical pressures are expressed in *volts*.

85. Expenditure of Energy in a Circuit.—It has been pointed out that when the external circuit is opened the energy of chemical action that does take place is transformed into heat within the cell. When the zinc has been properly amalgamated, practically no chemical action takes place within the simple voltaic cell just described. When the external circuit is closed the chemical action begins and continues so long as the current flows. In order that a current may flow continuously a difference of electrical pressure must be maintained between any two points of the circuit. The maintenance of this difference of electrical pressure requires a continuous expenditure of energy, and hence, continuous chemical action in the cell.

86. Experiment 23. To Study Polarization.

Apparatus.—

Volt-ammeter
Simple voltaic cell

Operation.—First clean the copper electrode of a simple cell with a piece of fine sandpaper; connect the simple voltaic cell to the voltmeter terminals as in Fig. 63. Close the switch at a definite time and read the voltmeter deflection at first every ten seconds, later at longer intervals. Keep the circuit closed for fifteen minutes.

Next remove the copper electrode from the solution and rub off the hydrogen bubbles under water. Also remove and clean the zinc. Replace the electrodes and take a new series of observations for fifteen minutes. Does the deflection fall off more or less rapidly than in the first part of the experiment? Why does the deflection of the voltmeter decrease with time?

87. Theory.—It is of course clear that the deflection of the voltmeter is caused by an electric current whose source is the cell. The deflection varies as the current strength changes. Any decrease in the current will be accompanied by a decreased deflection. It was noted in experiment 21 that gas bubbles arose from the copper electrode, when the two electrodes were connected. These gas bubbles first collect on the electrode and greatly increase the resistance of the cell. Any increase in the resistance decreases the current and consequently the deflection.

The e.m.f. of a cell is subject to changes produced by the current flowing through the cell. These changes, the causes of which are many, are called *polarization* and since they tend to decrease the current the effect is called *the counter e.m.f. of polar-*

ization. This counter e.m.f. must always be subtracted from the original e.m.f. in order to get the resultant e.m.f. of the cell. In all calculations of electrical quantities in a circuit containing a cell this resultant e.m.f. and not the original e.m.f. should be used.

In addition to an increase in resistance the hydrogen bubbles also create a counter pressure tending to drive the current in the opposite direction. These two effects together are called polarization. Thus in nearly every case, polarization in a voltaic cell is due to hydrogen bubbles collecting on the positive electrode.

Deposition on the electrodes of a substance different from that of the plates is one of the main factors of polarization. This is very apparent in the simple voltaic cell, consisting of a zinc and a copper plate in dilute sulphuric acid. When the circuit is closed, zinc goes into solution and hydrogen collects on the copper plate increasing the resistance and developing a counter pressure.

88. Kinds of Cells.—Cells are ordinarily classified as primary and secondary. A *primary cell* is one in which the electrical energy is produced by the chemical action which destroys one of the plates. This chemical action does not have to be preceded by electrolysis, but takes place immediately upon the assemblying of the parts of the cell and the closing of the circuit.

The *secondary,* or *storage,* cell is one in which the chemical action producing the current must be preceded by electrolysis. That is, before an electric current can be drawn from the cell the chemical condition of the plates must first be changed by sending a current of electricity through the cell in a direction opposite to that of the current given out by the cell. This process is called charging. Storage cells will be explained in connection with the chapter on electrolysis. Primary cells may conveniently be classified as single-fluid and two-fluid cells. That is, if the electrolyte is only one kind of a liquid and both electrodes are immersed in it, then the cell belongs to the first class. When each electrode is immersed in a separate liquid the cell belongs to the second class. This classification is for convenience only, and does not in any way represent a different method of generating or producing electrical current.

89. One-fluid Cells.—The most common single-fluid cell was devised by Leclanche, and consists of two forms. One form is shown in Fig. 65 and is the one commonly called the Leclanche cell. The essential parts of the Leclanche cell are a carbon rod for the positive electrode, a zinc rod for the negative electrode, a

solution of ammonium chloride for the electrolyte, and a glass jar. The carbon rod is placed in a porous earthenware cup packed in a mixture of manganese dioxide and coke. The electromotive force of this cell ranges from 1.4 to 1.7 volts on open circuit. The manganese dioxide is used as a depolarizer. The hydrogen on its way to the carbon plate is oxidized by the oxygen of the black oxide of manganese. Even with a depolarizer, the cell polarizes very rapidly and is, therefore, suited only for open circuit work; that is, for such work as the ringing of door bells. The other form of the Leclanche cell is ordinarily called the dry cell. In this form the carbon rod is in the center of a zinc cup. The cup acts as the negative electrode. The

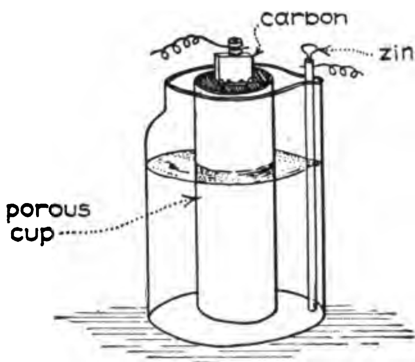

FIG. 65.

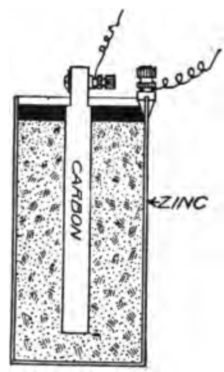

FIG. 66.

electrolyte is in the form of a paste of zinc oxide, zinc chloride, ammonium chloride, plaster of Paris, and water. To prevent evaporation, the cell is sealed with wax or some other cheap impervious matter. The electromotive force of the dry cell is about 1.4 volts; it polarizes rapidly and hence is best suited for open circuit work. A cross-section of a dry cell is shown in Fig. 66.

90. Edison Cell.—Another single-fluid cell uses for the positive electrode a plate of copper oxide, zinc for the negative electrode and a solution of sodium hydroxide (caustic soda) for the electrolyte. The top of the electrolyte is covered with a heavy oil to protect the zinc from attack by the solution of caustic soda. The pressure of this cell ranges from 0.5 to about 0.7 volt on closed circuit. The internal resistance of the Edi-

son cell is low and it has a comparatively high current capacity. It is suitable for either open or closed circuit work. A form of the cell is shown in Fig. 67.

91. Two-fluid Cells.—The most common two-fluid cell is the Daniell cell or some modified form of it. The original form of the Daniell cell is shown in Fig. 68. As shown the essential parts of the cell are a cylinder of copper for the positive electrode, a rod of zinc for the negative electrode, copper sulphate and zinc sulphate for the electrolyte, a porous cup and glass jar for container. The copper electrode is immersed in a saturated solution of copper sulphate. The zinc or negative electrode is placed within the porous cup and is surrounded by a weak solution of zinc sulphate. The purpose of the porous cup is to prevent the mixing of the two solutions. When the cell is first set up the solution around the negative electrode is dilute sulphuric acid. This acid acts upon the zinc, forming zinc sulphate, and accordingly the solution around the zinc grows denser with use. The hydrogen that is set free by the

Fig. 67.

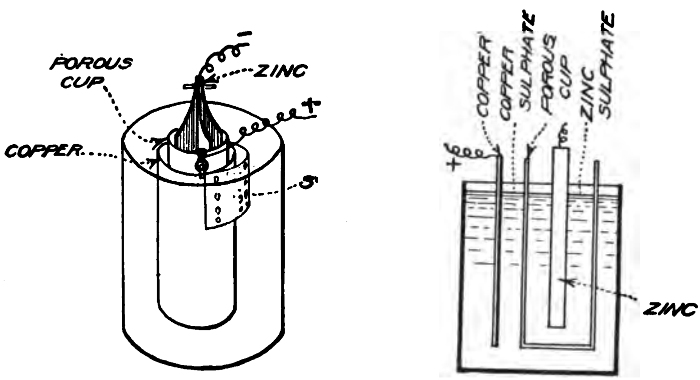

Fig. 68.

action of the acid upon the zinc passes through the porous cup and combines with the copper sulphate forming sulphuric acid and copper. The copper is deposited upon the copper plate or cylinder and hence no polarization takes place. We may thus consider the copper sulphate as a depolarizer. Since the

copper sulphate is constantly being decomposed when the cell is in action, the copper sulphate solution grows weaker with use. An excess of copper sulphate crystals is always put into the solution to insure continuous action.

92. Gravity Cell.—The gravity cell is merely a modification of the Daniell cell. In the gravity cell the positive electrode is made of copper and is placed at the bottom of the jar as shown in Fig. 69. Around the copper is placed a saturated solution of copper sulphate. Upon the copper sulphate is then poured dilute sulphuric acid within which is placed the negative electrode made of zinc cast in the shape of a crow's foot, whence the name "crowfoot gravity cell." The two solutions are of different densities; that is, zinc sulphate is lighter than the copper sulphate, and hence the solutions do not mix while the cell is in action. If the cell should be left open circuited for some time the solutions will mix and will have to be renewed and the zinc cleaned and amalgamated.

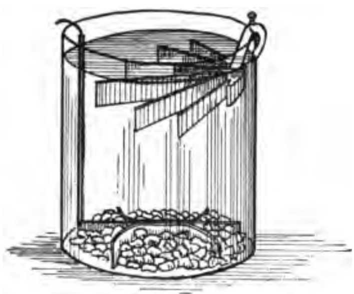

FIG. 69.

The electromotive force of the Daniell cell is about 1.1 volts, and as it does not polarize it is used very extensively on closed circuit work, that is, on circuits that require a continuous flow of current.

93. Experiment 24. Electromotive Force of Different Cells.

Apparatus.—

- Demonstration cell consisting of glass cup, porous cup, zinc, carbon, copper, lead, iron, aluminum, tin, and nickel strips
- Porcelain cap
- 1 oz. sulphuric acid
- Few crystals copper sulphate
- 2 oz. ammonium chloride
- Volt-ammeter
- Connectors and wire

Operation.—The purpose of this experiment is to determine the electromotive force of cells made of different materials. The student has already determined the e.m.f. of the simple cell.

Exactly in the same way set up a simple cell and measure the electromotive force when the following strips are used in pairs as electrodes:

Positive	Negative
copper	zinc
carbon	zinc
lead	zinc
aluminum	zinc
nickel	zinc
copper	lead
carbon	lead
carbon	aluminum
carbon	nickel

Be careful to read the voltage as soon as the circuit is closed. If this is not done, polarization will set in and the readings will be too low. Tabulate the results as follows:

Electrodes		Electrolyte	Voltage
Positive	Negative		
Copper, etc.	Zinc, etc.	Dilute sulphuric acid, etc.	0.85 volt, etc.

Next dissolve the ammonium chloride, commonly called sal-ammoniac, in about three-fourths of a tumbler of water. For electrodes use carbon and zinc. Having set up the cell again, measure its voltage as above described. Keep the circuit closed through the voltmeter for a time and observe the effect of polarization.

The foregoing experiments are all with single-fluid cells. One more experiment may be performed to show that a Daniell cell does not polarize. Dissolve the crystals of blue vitriol (copper sulphate) in one-half a tumbler of water. Leave this in the tumbler. Fill the porous cup about one-half full of pure water and add one-fourth as much sulphuric acid. Place an amalgamated zinc rod within the porous cup for the negative electrode and a copper strip in the solution of copper sulphate for the positive electrode. Set the porous cup inside of the tumbler and connect the electrodes to the voltmeter and

observe the deflection. Keep the circuit through the voltmeter closed for some time and observe if the deflection decreases. Record all of the facts observed.

94. Theory.—The foregoing experiments show that the pressure a cell develops depends upon the material of which the cell is made. The size of the plates has nothing to do with the value of the electromotive force on open circuit. The size of the plates will, of course, determine the capacity of the cell to deliver current, but not the pressure.

The experiments also show the single-fluid cells, such as the Leclanche cell, etc., polarize rapidly, and that the Daniell cell does not polarize. The reason for this is the fact that as a result of the electro-chemical action within the cell, copper is deposited upon the copper electrode. The hydrogen combines with the copper sulphate, producing sulphuric acid and liberating copper. The solution around the negative, or zinc, electrode gradually increases in density while that around the positive electrode decreases in density. This is the reason why an excess of copper sulphate crystals is required around the copper electrode.

Fig. 70.

The fact that the Leclanche cell, and others like it, polarizes rapidly makes it suitable only for intermittent work, that is, for work where the circuit remains closed for only a brief instant. During the time that the circuit is opened the polarization disappears and the cell is again ready for use.

The Daniell cell, on the other hand, does not polarize and accordingly it is suitable for closed circuit work such as telegraphy.

95. Practical Application of Cells.—There are so many operations for which primary cells are used that only a few can be given. In many domestic operations such as the ringing of door bells, operation of dampers, and heat-regulating devices, some form of primary cell is used extensively. In the operation of the telephone and telegraph, and in the operation of the ignition systems of gas and gasoline engines, great numbers of the cells are used. Steam railway signal systems are often operated by the Edison cells, and another application of the primary cell which is greatly on the increase is the pocket flash lamp, one form of which is shown in Fig. 70.

RECAPITULATION

1. A *primary cell* is a combination of electrolyte, electrodes, and container such that the chemical action taking place between electrodes and electrolyte is the primary or immediate source of the electric current.
2. By *amalgamation* is meant the process of coating zinc with mercury.
3. By *local action* is meant the destructive action of electric currents set up between the impurities in the zinc electrode and the zinc itself. Amalgamation covers these impurities with mercury and thus decreases these currents.
4. A *conductor* is a material along or through which a current of electricity can be transferred.
5. The *electromotive force* or *electrical pressure* of a cell is the cause of the flow of an electric current when the circuit is closed. It is analogous to water pressure.
6. The *pressure* a cell develops depends upon the material of which it is made.
7. The unit of electrical pressure is the *volt*. The *volt* is equal to $\frac{100000}{101880}$ of the pressure of the Weston standard cell at 20 degrees centigrade.
8. *Polarization* is the decrease in the resultant pressure of a cell. It is caused by the hydrogen and the positive electrode.

CHAPTER VI

ELECTROLYSIS

96. Introduction.—The word *electrolysis* in ordinary language is used in two senses. One use of the word has reference to the corrosive action of the electric current on underground or imbedded iron pipes or rods. The second use of the word has reference to the decomposition of liquids by the passage of an electric current. This is the meaning of electrolysis as used in the following discussion.

97. Liquid Conductors.—With reference to the manner in which liquids conduct electricity they can be divided into three classes:

1. *Insulators.*—In some cases liquids offer a very high resistance to the flow of current and act as insulators. Such is the case with paraffin oil, turpentine, etc.

2. *Conductors.*—Some liquids, like mercury and molten metals, conduct electricity in the same manner as solid conductors. When electricity is passed through these, no decomposition or chemical action takes place.

3. *Electrolytes.*—Solutions of acids, bases, or salts conduct electricity by undergoing decomposition, when electric current is passed through them. Such solutions are called electrolytes.

98. Experiment 25. Electrolytic Decomposition.

Apparatus.—

Two dry cells
Tumbler
A little sulphuric acid
Some copper sulphate crystals

Operation.—Take a tumbler and fill it about half full with pure water. Connect the two dry cells in series, that is, connect the carbon rod in the center of one cell with the zinc cup of the other cell. To the two remaining terminals connect two copper wires about 1 ft. long each. Dip the exposed ends of the copper wires into the water in the tumbler, keeping them about 1 in. apart as indicated, in Fig. 71. Do any gas bubbles rise from either wire? To which class of liquids does pure water belong?

Carefully pour about a thimbleful of sulphuric acid into the tumbler of water. Stir the mixture with a stick, then again dip the two exposed ends of the wires into the liquid. Does any gas rise from the wires? To be sure that the gas is not due to chemical action between acid and copper wires, take two wires that are not connected to the dry batteries and dip them into the solution. Is the action the same as when wires connected to the cell were dipped into the liquid? Repeat the experiment again and see at which wire most gas collects. Is it the wire connected to the carbon or zinc electrode of the cells?

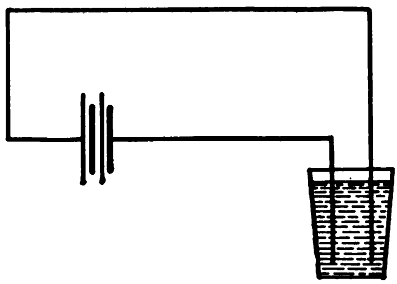

Fig. 71.

When you have satisfied yourself on this point, throw the acid solution away. Dissolve a large crystal or two of copper sulphate in about half a tumbler of water. Wrap the end of the wire that is connected to the negative electrode around one end of a nail, or use one of the connectors for making this connection. Dip the nail and the other wire into the solution of copper sulphate as indicated in Fig. 72. After ten or fifteen minutes, withdraw the nail and examine it. Has it changed color? Is it coated with rust or copper? Where did the coating come from? Connect the nail to the other electrode of the dry cells and again immerse it in the solution as before. Leave it there for about 15 minutes and then examine again. Does it still have the dull red coating? What has become of it?

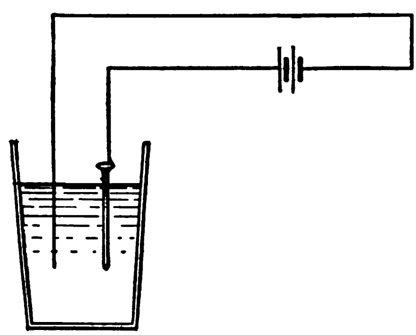

Fig. 72.

Connect one nail to each electrode and dip both of them into the solution. After about 15 minutes withdraw both and examine them. Are they both coated? To which terminal of the cell is the coated one connected? Does gas escape from the elec-

trolytic cell? The tumbler, solution and electrodes, in this case nails, are called an electrolytic cell.

To which class of liquids do solutions of sulphuric acid and copper sulphate belong?

99. Theory.—If the student has carefully performed the foregoing experiment, he has learned that pure water is practically a non-conductor, but when a solution of sulphuric acid is made it becomes a fairly good conductor. The transfer of electricity through the solution is explained on the supposition that in the process of solution the sulphuric acid is dissociated. This will be explained more fully later.

100. Anode and Cathode.—The terminal by which a current enters the electrolytic cell is called the *anode*, and the terminal by which the current leaves the cell is called the *cathode*. The solution is the electrolyte as explained in the preceding chapter.

The student observed that when the current is passed through the solution of sulphuric acid, gas collects at each terminal, but that more accumulates at the cathode than at the anode. The gas that collects at the anode is oxygen and the gas collecting at the cathode is hydrogen. In the same way when current is passed through the copper sulphate solution, copper is deposited at the cathode while the anode remains clean. It is thus seen that some substances travel with the current while others move against the current.

101. Dissociation Theory.—Within recent years a theory has been advanced to explain the action of an electrolytic cell. While this theory has not been proved in all its phases, nevertheless, it is helpful in giving an understanding of electrolysis and electrolytic processes. The elements of the theory are as follows: In the preceding experiment the student learned that pure water is practically a non-conductor. The same is true of pure sulphuric acid; nevertheless a mixture of the two conducts electricity fairly well. Sulphuric acid is a compound consisting of hydrogen (H), oxygen (O), and sulphur (S). The chemical symbol for it is H_2SO_4. According to the dissociation theory where sulphuric acid is dissolved in water the sulphuric acid is decomposed or dissociated into two groups of atoms. One group (H_2) is charged positively and the other group (SO_4) is charged negatively. These charged groups of atoms are called ions. When the solution is subjected to an electrical pressure, the hydrogen ions move from higher to lower pressure; that is, toward the cathode

where they deposit their charge and escape as pure hydrogen atoms. The sulphions (SO_4) move against the current and at the anode they deposit the negative charge. When freed from the negative charge, they attack the water, combining with the hydrogen, while oxygen is set free.

102. Faraday's Law.—We have just learned that when electricity is passed through a salt solution, the metal of the salt is deposited upon the cathode. After many exhaustive experiments Faraday formulated two laws which express the relation between the quantity of electricity passing and the mass or weight of metal deposited. These relations are known as Faraday's Laws, and are as follows:

1. When electricity is passed through a solution, the mass of the decomposed solution is proportional to the quantity of electricity passing.

2. The mass of any substance liberated by a given quantity of electricity is proportional to the chemical equivalent of the substance.

The first law means that a given current of electricity, flowing for a given time, will always deposit the same mass or weight of a given element from a solution, irrespective of the concentration of the solution that contains the element or of other conditions.

According to the second law, the mass of the substance deposited will depend upon its combining weight, which is called chemical equivalent. Thus, when a solution of copper salt is used as the electrolyte, the mass of copper deposited will depend on whether a cupric or cuprous salt is used. The chemical symbol for cupric chloride is $CuCl_2$ and for cuprous chloride $CuCl$. From this it will be seen that two atoms of copper in the cuprous compound take the place of one atom in the cupric compound. The combining weight is twice as great, and twice as much copper will be deposited by a given current from a cuprous solution as from the cupric solution. The law also states that if solutions of different compounds be decomposed, the weight of material deposited by a given current is proportional to the combining weight of the materials or elements forming the compounds. Thus, 1 ampere sent through a solution of silver nitrate for an hour will deposit 4.025 grm. of silver. The same current sent through a solution of copper sulphate will deposit only 1.184 grm. of copper in one hour. These laws are the fundamental principles of the operation of electro-chemical measuring instru-

ments. The electro-chemical equivalents of some metals are given in the following table:

TABLE IV

Metal	Electro-chemical equivalent in milligrams per coulomb
Aluminium	0.0936
Copper	0.6588
Copper	0.3290
Gold	0.6818
Iron	0.2894
Iron	0.1929
Lead	1.0731
Nickel	0.3040
Silver	1.1180
Zinc	0.3385

It is noticed that two values are given in the table for copper and iron. This is because each of these has different combining powers, as explained above. The value 0.3290 for copper usually applies when copper is deposited in an electrolytic cell. The table may be reduced to English units by remembering that 1 grm. is equal to 0.0353 oz., avoirdupois.

103. Electric Current.—We have already used the words *electric current* several times without explanation. Perhaps an explanation will not greatly aid in giving an understanding of the physical phenomena, nevertheless it will be attempted.

The transfer of electrical energy along wires or conductors is in many respects like the transfer of energy by water when flowing through pipes. For this reason many words that are used in describing the flow of water are used when the transfer of energy by electrical means is considered.

When water flows through pipes, the energy transferred by it in a given time depends upon the current and head or pressure. The current is defined as the number of cubic feet or gallons of water flowing past any point in a second or some other unit of time. The current is then the rate of flow of water.

Electrical energy may be transferred along or by means of a conductor. The transfer of energy is said to be by means of a current of electricity. Thus the rate of flow of electricity is also called a current. An electric current may then be defined as a continuous transference of electrical energy from its source to other parts of the circuit.

In measuring a water current it is possible to measure the quantity of water discharged and thus the rate of flow can be determined by dividing the total quantity by the time of flow. It is not practical to measure an electric current in this way. The electric current is measured by means of its electrolytic, magnetic, or heat effects. The unit current has been defined in accordance with Faraday's first law.

104. Definitions.—The *ampere* is the unvarying electric current which, when passed through a standard solution of silver nitrate, deposits silver at the rate of 0.001118 grm. per second. An ampere will thus deposit 4.025 grm. of silver per hour.

Coulomb.—The coulomb is the unit quantity of electricity and is the quantity of electricity given by one ampere in one second. Thus according to the definition of ampere given above, when one coulomb of electricity is passed through a standard solution of silver nitrate, 0.001118 grm. of silver are deposited upon the cathode.

Electro-chemical Equivalent.—The mass of any metal deposited by one coulomb of electricity is called the electro-chemical equivalent. Thus in the table on page 109 the electro-chemical equivalents are given in milligrams. One milligram equals 0.001 grm.

EXAMPLES

1. How many grams of copper will be deposited by 100,000 coulombs of electricity?

   Solution.—1 coulomb deposits 0.000329 grm. 100,000 coulombs will deposit $100{,}000 \times 0.000329 = 32.9$ grm.

2. A steady current is passed for one hour through a silver nitrate solution. If 13.68 grm. of silver are deposited, what is the current?

   Solution.—In one hour 1 ampere deposits 4.025 grm. Hence current required to deposit 43.68 grm. is $43.68 \div 4.025 = 10.85$ amperes.

105. Secondary or Storage Cells.—The principle of electrolysis is applied in producing a chemical change which under proper conditions is reversed and the chemical energy is converted into electrical energy or energy of the electrical current. Electrolytic cells which are used for this purpose are called *secondary* or *storage cells.* The essential principles will be made clear by the following experiment.

106. Experiment 26. Principles of the Storage Battery.

Apparatus.—

Two 1 in. × 6 in. strips of lead
Tumbler
Dilute sulphuric acid
Ammeter
Electric bell

Operation.—Fasten the two lead strips on opposite sides of a dry piece of wood $\frac{1}{2} \times 1 \times 4$ in. Between each lead strip and the wood clamp a piece of copper wire for connections, or drill a hole in each strip and fasten a wire in it. The holder of the experimental cell may be used in place of the block of wood.

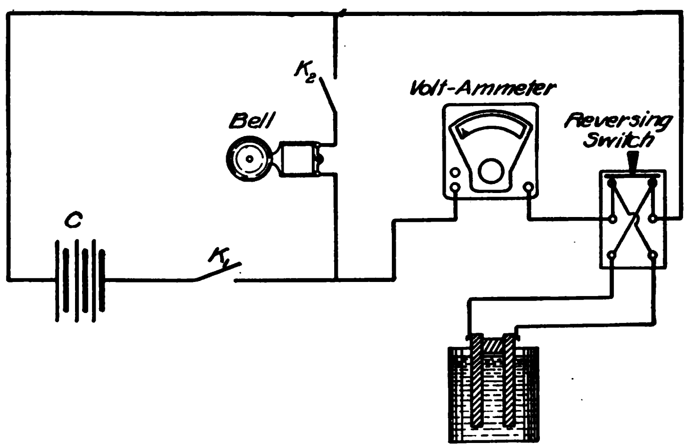

Fig. 73.

Immerse the two lead strips in a solution consisting of one part of sulphuric acid to ten parts of rain water. Connect three dry cells in series and then arrange the apparatus as shown in Fig. 73. Close switch K_1 and leave K_2 open. As the current flows, bubbles will be seen to arise from the cathode, while the anode will begin to turn a dark brown. Observe carefully the behavior of the ammeter. After about twenty minutes open key K_1 and close K_2. Does the bell ring? Observe the deflection of the ammeter. Is it in the same direction as before or in the opposite direction? Reverse the switch S and observe how rapidly the current decreases.

107. Theory.—This experiment illustrates the principles of the storage cell. The student observed that the color of the

anode changes from the natural color of lead to brown. This brown coating is a compound of lead and oxygen, called lead peroxide with a chemical symbol (PbO_2). This lead peroxide is formed by the action upon the plate of the oxygen. When the charging circuit is opened and the circuit through the bell is closed, the cell acts exactly like a primary cell and furnishes a current until all of the peroxide is used up. This current is due to the conversion of the lead peroxide into metallic lead. This is also a chemical change. Properly speaking, there has been no storage of electricity but only a storage of energy. In other words, the energy of the current which is sent into the cell is expended in producing chemical changes upon the electrodes, and therefore, it remains as potential energy until a

FIG. 74.

FIG. 75.

wire connects the two plates, when it again appears as the energy of the electric current. In a good storage cell the energy that has been expended in charging may remain for weeks as potential energy without serious loss.

In addition to the simple reaction described there are other reactions or changes taking place both on charging and discharging. Some of these are not very well understood and the one mentioned is undoubtedly the one to which the action of the storage cell is principally due.

108. The Lead Storage Cell.—The only important difference between the lead commercial storage cell and the experimental one used is that the commercial cell is provided in the making with a much thicker coat of the lead peroxide on the positive plate, Fig. 74, and of the spongy lead, lead oxide (PbO) on the

negative plate, Fig. 75. This material is pressed into the interstices in the plates. A complete lead storage cell also called accumulator, is shown in Fig. 76.

The lead plates have little rigidity and easily become warped. If discharged or charged too rapidly, the plates become hot and buckle, that is twist out of shape, thus short circuiting the cell and destroying its usefulness. If the cell is allowed to stand discharged for a few weeks, the lead sulphate formed

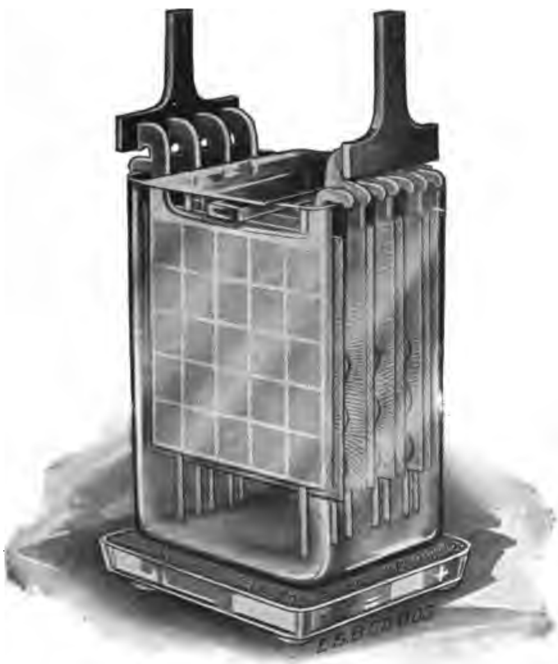

Fig. 76.

on the negative plate during discharge becomes hard; this interferes with the proper working of the cell. Unless storage cells are watched and kept in good condition, they deteriorate rapidly and quickly get out of order. All contacts and metal parts near the cell must be lead covered to protect them from the action of the sulphuric acid. For permanent installations the containers are of glass, but where the cell is to be portable the container is usually a rubber jar, Fig. 77. The efficiency

of the lead cell is about 75 per cent; that is, only about three-fourths of the energy used on charging can be obtained for useful work on discharging.

Fig. 77.

The voltage of the lead storage cell depends upon the character of the electrodes and the density of the electrolyte. On charge and discharge the voltage of the lead storage cell changes as represented by curves, Fig. 78. The voltage should never be allowed to drop below 1.7 volts, for if it does it will become so badly sulphated that it will be practically impossible to restore the cell to normal condition.

109. The Nickel-Iron Cell.—The lead storage battery has several disadvantages in practical use. Among the most prominent may be mentioned the following: the giving off of acid fumes which makes necessary special construction of rooms for

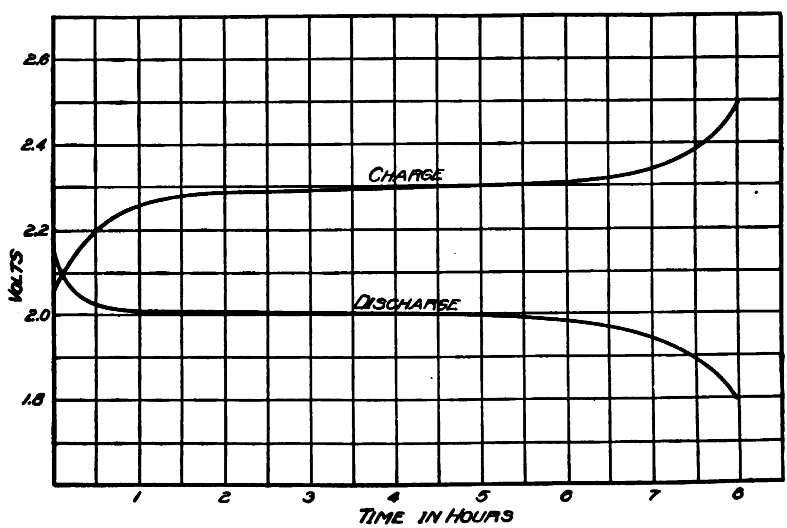

Fig. 78.

PLATE 4.—A storage battery installation for the Goldfield Consolidated Mines Co., Goldfield, Nevada.

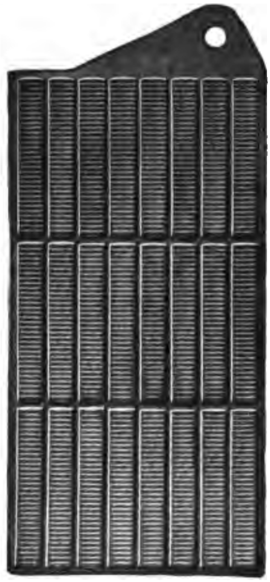

FIG. 79.

FIG. 79a.

housing the battery and also necessitates extra ventilation; the rapid deterioration of the plates; excessive weight when used for automobiles, etc. Many attempts have been made to either remove these objectionable features, or to discover some substances out of which a cell could be made which will not inherently possess these disadvantages. The storage cell invented and designed by Mr. Thomas A. Edison is free from some of the foregoing defects. The container of the Edison storage cell is a jar of nickel-plated steel which is not readily broken. The electrodes are of iron and nickel and the electrolyte is a solution of caustic potash.

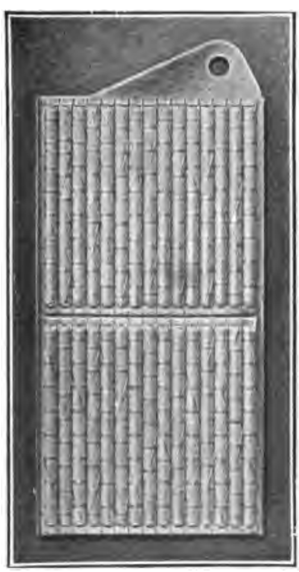

FIG. 80.

The negative plate, Fig. 79, con-

sists of a gridiron of steel with a paste of iron oxide in the pockets. The pockets are made of thin nickel-plated steel, perforated with fine holes. The positive plate, Fig. 80, is a framework of steel within which are some thirty steel tubes about the size of lead pencils, Fig. 80a. These tubes are perforated and contain alternate layers of nickel oxide and nickel, the nickel serving the purpose of a conductor.

Fig. 80a.

Fig. 81.

In a cell the positive and negative plates are assembled alternately, the positive plates are all connected together and likewise the negative plates are connected together in order to increase the capacity of the cell. The complete cell is shown in Fig. 81.

The advantages of the nickel-iron cell are its mechanical strength, weak or comparatively harmless electrolyte, and relatively high output per pound of cell. The voltage of the cell is only about one-half as high as that of the lead cell, and its efficiency is only about 60 per cent. when charged and discharged in accordance with the curves shown in Fig. 82.

110. Electroplating.—The fact that the solution of a metal salt is decomposed by the passage of an electric current through it has made possible the process of plating or coating the baser metals with copper, gold, silver, nickel, etc. The process in general consists in immersing the body to be plated in a solution of a salt of the metal with which the body is to be plated. The anode is nearly always made of the same substance

as that to be deposited from the solution. The body to be plated is always the cathode. For detailed descriptions the student is referred to handbooks on electroplating.

111. Voltages for Electroplating.—Experiments show that the most suitable voltages for electroplating are about as follows:

TABLE V

Copper in sulphate	1.5 to 2.5 volts
Copper in cyanide	4.0 to 6.0 volts
Silver in cyanide	1.0 to 2.0 volts
Gold in cyanide	0.5 to 3.0 volts
Nickel in sulphate	2.5 to 5.5 volts

112. Critical Current Density.—From theoretical considerations one might conclude that the higher the current the more

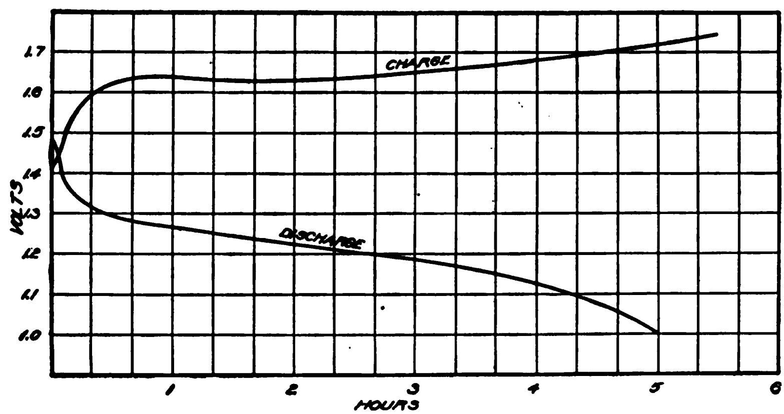

Fig. 82.

rapidly would the process of electroplating proceed. It is true that the decomposition of the solution would proceed at a higher rate the higher the current density, but practical difficulties are encountered if the current density is too high, or above a certain value called the *critical current density*. A current greater than the critical value results in depositing the hydrogen in conjunction with the metal, and, as a consequence, the deposited metal will not adhere and make a smooth coating. By rotating the cathode a much higher current density may be used and still obtain good results.

113. Electrotyping.—In the process of making plates for printing by electrolytic deposition, the page is first set up in common

type. An impression is then made in wax. This mold is then coated with powdered graphite to make it a conductor, after which it is ready to be suspended as the cathode in a copper plating bath, the anode being a copper plate and the electrolyte a solution of copper sulphate. When a film of the desired thickness has been formed, the mold is removed by pouring hot water on it, after which the film is backed by the type metal to give it the necessary rigidity. A good copper plating bath can be made as follows:

Dissolve about 20 grm. of copper acetate in 500 c.c. (a little over one pint) of water. Dissolve 20 grm. potassium cyanide, 25 grm. sodium sulphate crystals, and 17 grm. of sodium carbonate crystals in another 500 c.c. of water. Then add the first solution to the second one. For plating, a current density of

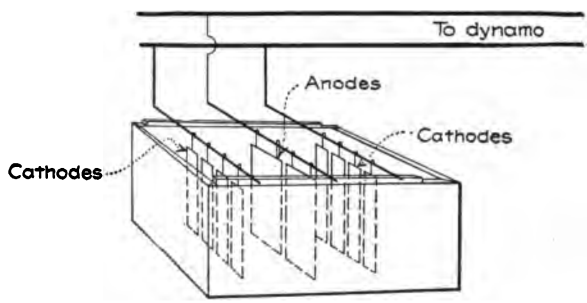

FIG. 83.

0.003 ampere per square centimeter is then used with 3 volts at the terminals of the cell.

114. Gold and Silver Plating.—Gold and silver plating are carried on in much the same manner. Three solutions are used in gold plating to give the different coloring effects known as California, green and red gold. In making the solutions the following salts are dissolved in a mixture of nitric and hydrochloric acid.

An alloy of 22 parts gold and 2 parts silver is used for California gold; an alloy of 16 parts gold and 8 parts silver is used for green gold; and an alloy of 16 parts gold and 8 parts of copper for red gold. The anodes are of pure gold, and a difference of electrical pressure of 5 volts is maintained across them.

115. Refining of Metals.—Another important electrolytic process is the process of refining copper. Fig. 83 shows the

arrangement of a tank or bath for this purpose. The copper to be refined is suspended in a copper sulphate solution and current is sent through them to the cathodes. As the anodes of copper are eaten away the impurities fall as residue to the bottom of the tank and pure copper is deposited on the cathode. Other metals can also be refined in the same way.

116. Some Other Electrolytic Processes.—When electrical energy is comparatively cheap, as at Niagara Falls and other water powers, various electrolytic processes are carried on. Caustic soda, metallic sodium, aluminum, potassium chlorate, and many other substances are manufactured on a large scale by modified electrolytic processes. Recently there has been developed and placed on the market an apparatus for the purification of air in class-rooms, churches, and other buildings. This apparatus generates ozone by an electrical discharge in the air. The ozone then acts chemically on the impurities reducing them to a harmless condition. It is claimed that the ozonator, as the apparatus is called, greatly improves the sanitary conditions wherever indoor air is breathed. The appearance of one form of ozonator is shown in Fig. 84. For more detailed explanations of electrolytic processes the student is referred to books on electro-chemistry:

Fig. 84.

RECAPITULATION

1. By *electrolysis* is meant the process of chemical decomposition by the passage of the electrical current.
2. According to their electrical properties liquids may be divided into three classes, *insulators, conductors,* and *electrolytes.*
   (a) Liquids act as *insulators* when they offer very high resistance to the flow of electricity.
   (b) Liquids act as *conductors* when their conductivity is like that of solid conductors.
   (c) Liquids are called *electrolytes* when they suffer decomposition by the passage of an electric current through them.

3. An *electrolytic cell* is a combination of container, electrolyte and electrodes.
   (a) The *anode* of an electrolytic cell is the electrode by which current enters the cell.
   (b) The *cathode* is the electrode by which the current leaves the electrolytic cell.
4. *Faraday's laws* of electrolysis express the relation between the mass of the electrolyte decomposed and the quantity of electricity causing the decomposition. They are:
   (a) When electricity is passed through a solution, the mass of the solution decomposed is proportional to the quantity of electricity passing.
   (b) The mass of any substance liberated by a given quantity of electricity is proportional to the chemical equivalent of the substance.
5. An *electric current* is the name given to a continuous transference of electrical energy from its source to other parts of the circuit.
   (a) The practical unit of electrical current is the *ampere* and is defined as that current which, when passed through a standard solution of silver nitrate, deposits silver at the rate of 0.001118 grm. per second. An ampere will thus deposit 4.025 grm. (=0.1408 oz., avoirdupois) per hour.
6. The *coulomb* is the unit quantity of electricity, and is the quantity of electricity given by 1 ampere in one second.
7. By *electro-chemical equivalent* is meant the mass of any metal deposited by one coulomb of electricity.

CHAPTER VII

RESISTANCE

117. Introduction.—So far we have discussed the generation of an electromotive force both by chemical and mechanical means. It has also been stated that when a source of electromotive force is connected to a circuit, and the circuit is closed, an electric current will flow. Nothing, however, has been said concerning the relation between the strength of the current, the electromotive force, and other quantities of the circuit.

We shall now investigate and determine some of these relations. In order to do this we must discuss another quantity which plays an important part in determining the flow of current in a circuit but which so far has been barely mentioned.

118. Electrical Resistance.—A clear understanding of this quantity will be perhaps best obtained by comparing the resistance a conductor offers to the flow of an electrical current with the resistance offered by a pipe to the flow of water in that pipe.

If the pipe be connected to a tank in which the water is kept at a constant level, a definite quantity of water will flow through it in unit time. This quantity will remain constant so long as the height of the water in the tank remains constant. The pressure exerted at the pipe is constant and the current is constant. If, however, a pipe of the same length but of larger diameter be connected to the same place on the tank, a greater current will flow. This is explained by saying that the larger pipe offers less resistance to the flow of water.

Again, if a short pipe be replaced by a long one of the same diameter the current will be less; that is, a smaller quantity will flow through the pipe in unit time. This is explained by saying that a long pipe has a greater resistance than a short one of the same diameter.

If we replace an iron pipe with a smooth inner surface by a wooden one with a rough inner surface, the current in the wooden one will be less even though the diameters of the two pipes are

equal. In this case the materials of which the pipes are made are different, and the one with rough inner surface, or the one of wood, offers the higher resistance. Summarizing these facts with reference to water pipes we find:

1. A large pipe offers less resistance to the flow of water than a small one of the same length. In other words, the same pressure will force a greater current through a large pipe than through a small one.

2. A long pipe offers greater resistance to the flow of water than a short one of the same diameter. In other words the same pressure will force a larger current through a short pipe than through a long one.

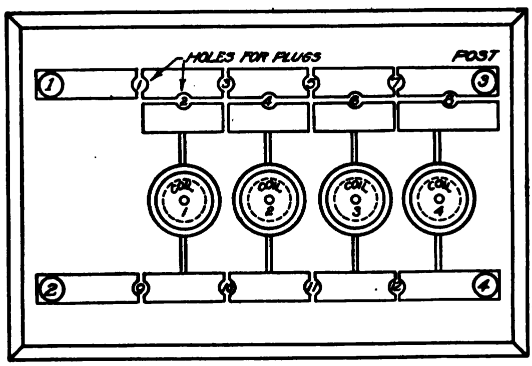

FIG. 85.

3. The resistance offered by two pipes of equal lengths and diameters depends upon the character of their inner surfaces; that is, upon the material of which the pipes are made.

Whether or not these same relations hold in an electrical circuit we shall now investigate.

119. Experiment 27. To Determine Relation between Current and Length of Conductor When Pressure is Kept Constant.

Apparatus.—

Volt-ammeter
Resistance board
Two dry cells

Operation.—A diagram of the resistance board to be used in this experiment is shown in Fig. 85. As there shown this board consists of four coils—1, 2, 3, and 4—mounted in such a

way that they can be connected singly, in series, or in parallel as desired. The data for the wires are as follows:

TABLE VI

Coil	Length	Number	Diameter in mils	Area in circular mils	Material
1	600 cm.	36	5.00	25.00	Copper.
2	300 cm.	30	10.03	100.5	German silver.
3	300 cm.	30	10.03	100.5	Copper.
4	300 cm.	36	5.00	25.00	Copper.

To connect coil 1 in series with a source of electromotive force, connect the dry cell to binding posts 1 and 2, Fig. 85, insert plugs 1, 2, and 9, and withdraw plug 10. When this is done the current will flow through coil 1 only. Inserting plug 10 and withdrawing plug 11 connects coils 1 and 2 in parallel. That is, the current can cross from binding post 1 to binding post 2 by two paths. Inserting plug 11 and withdrawing plug 12

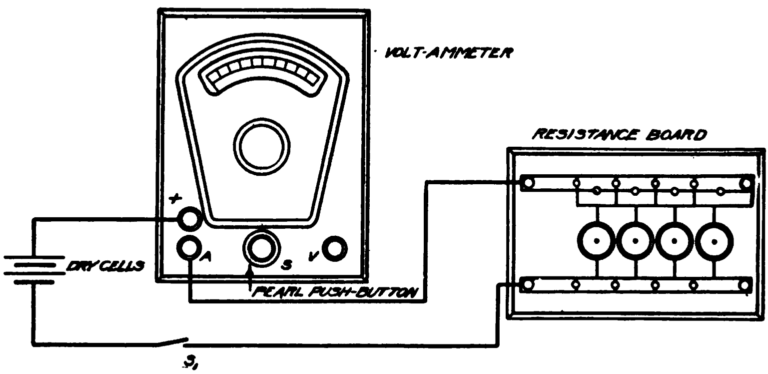

FIG. 86.

connects coils 1, 2, and 3 in parallel. Inserting plug 12, when other plugs are in, connects all of the coils in parallel.

If it is desired to connect coils 1 and 2 in series, connect the cell to posts 1 and 3, and withdraw plugs 3 and 11. The current will then flow from binding post 1 to coil 1, from coil 1 across plug 10 to coil 2 and then through coil 2 and bars back to binding post 3. To connect all coils in series leave the cell connected to binding posts 1 and 3, and remove plugs 3, 7, and 11. To connect coils 1 and 4 in series leave the battery connections

as just explained and remove plugs 4, 5, and 6. Plugs 10, 11, and 12 must be inserted. If it is desired to connect coils 1 and 2, and 3 and 4 in parallel and then the two parallel circuits in series, connect the battery to binding posts 1 and 3, and withdraw plug 5.

In using the resistance board follow instructions carefully as this also may be damaged by careless usage or large currents. Study the connections carefully before beginning the experiment.

Connect two dry cells, the board, and volt-ammeter as shown in Fig. 86. That is, connect the carbon of one dry cell to the + binding post of the volt-ammeter; connect the zinc cup of this dry cell to the carbon of second cell, and the zinc cup of the second cell to one side of a switch. The other side of the switch must be connected to binding post 2 of the resistance board as shown in Fig. 86. Finally, connect binding post 1 of the board to binding post *A* of volt-ammeter. When you have these connections made, withdraw plug 10, Fig. 85, push down pearl push-button on volt-ammeter, and close switch *S*. Keep switch closed until pointer quits swinging, then read the deflection and immediately open the switch. Repeat this five times and record your readings thus:

Experiment 27

Two dry cells in series; Current through coil 1

No. of reading	Current
1	0.30 ampere
2	0.27 ampere
3	0.30 ampere
4	0.30 ampere
5	0.25 ampere
	1.42 ampere
Mean	0.284 ampere

Repeat the experiment with coil 4 only. Then disconnect the wire from binding post 2, Fig. 85, and connect it to binding post 3. Withdraw plugs 3, 4, and 6. Such a connection will leave coils 1 and 4 in series. Take five readings as before and record. If you find that some of the readings differ greatly, try again until you are certain that the readings are correct.

In order to get accurate readings it will be necessary to have the volt-ammeter level. The pointer is not accurately balanced

and unless care is taken to keep the meter horizontal the readings will be in error.

120. Theory.—The results of the foregoing experiment show clearly the change of current when the length of conductor is changed and pressure remains constant. The wires of coils 1 and 4 are of copper and of exactly the same diameters, but of different lengths, see table page 125. The wire on spool 1 is just twice the length of that on spool 4. Does the current vary

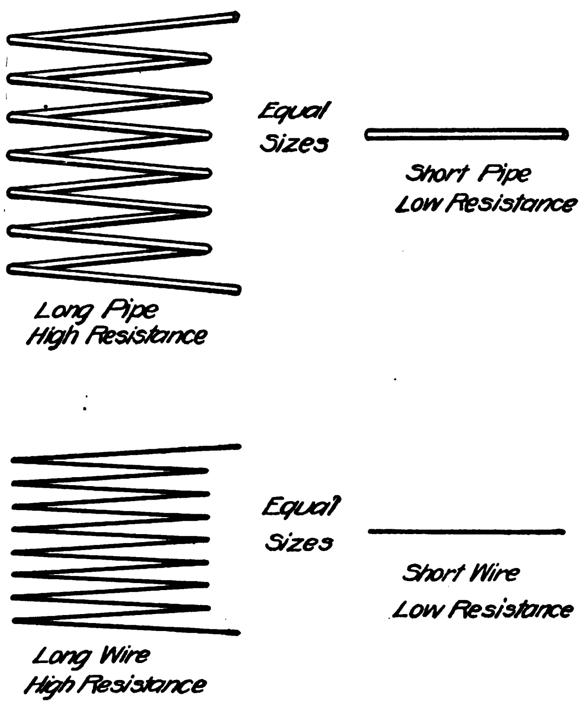

Fig. 87.

with the length? How? If the experiment has been carefully performed, the current through coil 4 should be about twice that through coil 1.

When coils 1 and 4 are connected in series the total length of the wire is three times that of the wire on spool 4. What should the current be if it varies inversely as the length? Is the current what you expected it to be?

The experiment shows that the current decreases as the length

of wire through which it flows increases. This amounts to the same thing as to say that the opposition offered by a wire to the flow of current increases with the length of the wire. This opposition is called resistance and hence the resistance of a conductor is directly proportional to its length. This is clearly analogous to the resistance offered by a pipe to the flow of water through it, the longer the pipe the smaller the current. This analogy is brought out clearly by Fig. 87.

121. Experiment 28. To Study the Relation between Size of Wire and Current.

Apparatus.—Same as in preceding experiment.

Operation.—This experiment is to be performed exactly like experiment 27, but instead of using coils 1 and 4, use coils 3 and 4.

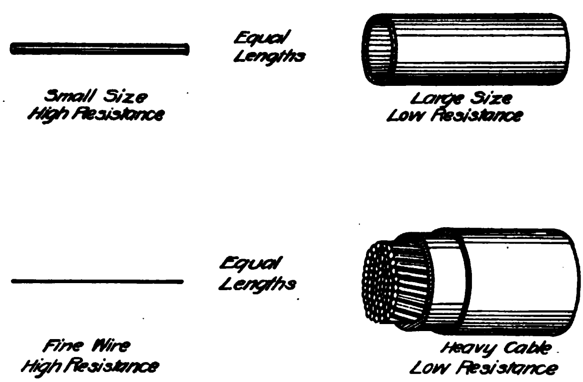

FIG. 88.

First connect two dry cells, board, meter, and switch as in Fig. 86. Withdraw plugs 2, 4, and 12. When this is done the current will flow through coil 3 only. Hold down the push-button on the ammeter, and close the switch. Read the instrument as soon as the pointer comes to rest, then open the switch. Coil 3 does not have a high resistance or a large current-carrying capacity, and hence, the current must not be permitted to flow through it for more than an instant. The pearl push-button on the meter does not break the main circuit and when this is released the current will still continue to flow through the coil on spool 3 unless switch S is opened. It is thus necessary always to open switch S as soon as possible.

Keep the dry cells connected as before. Remove plugs 2, 4,

and 6, replace 12 and repeat the experiment. Record the deflections exactly as in the previous experiment. Do the two coils give different deflections? Which coil gives the greater deflection?

122. Theory.—Coils 3 and 4 are of copper, each 300 cm. long. Coil 3 is of No. 30 wire which has a diameter of 0.01003 in. or 10.03 mils, a mil being 1/1000 in. Coil 4 is of No. 36 wire, and has a diameter of 0.005 in. or 5 mils. The results of the experiment show that the current through the larger, No. 30, wire is greater than the current through the No. 36 wire. The analogy between the resistance offered by two different-sized pipes to the flow of water, and two different-sized wires to the flow of an electric current is shown in Fig. 88. The exact relation between the size of wire and resultant current where the pressure is kept constant is not so evident. To determine this relation we must first show how wires are measured.

123. Wire Measurement.—In this country the length of wire is usually given in feet, and the size is specified either by diameter, cross-sectional area, or gage number. The units used for the measurement of the diameter and cross-sectional area are not the inch and square inch, but the mil and circular mil.

The Mil.—The unit of length in measuring the diameter is the 1/1000 (=0.001) in. and is called the mil. A 1-in. cable has a diameter of 1,000 mils. The diameter of a wire 0.25 in. is equal to 250 mils, etc.

Circular Mils.—A circle whose diameter is 0.001 in. (=1 mil) is said to have an area of 1 circular mil. Since the areas of two circles having different diameters are to each other as the squares of their diameters, to express the cross-section of any wire in circular mils, when its diameter in mils is given, all that is necessary is to square the diameter, that is, multiply the diameter by itself.

EXAMPLES

1. What is the cross-sectional area in circular mils of a wire 1/4 in. in diameter?

Solution.—

1/4 in. = 0.25 in.
0.25 in. = 250/1000 = 250 mils
Area in circular mils (C. M.) equals diameter squared
Dia. = 250 mils
$250^2 = 250 \times 250 = 62{,}500$ C. M.

2. A number 0000 wire has a cross-sectional area of 211,600 circular mils. What is its diameter in mils and in inches?

Solution.—Since the cross-sectional area in circular mils is equal to the square of the diameter in mils, the diameter in mils must be equal to the square root of the cross-sectional area. In symbols

$$D^2 = \text{area}$$
$$\text{and } D = \sqrt{\text{area}}$$
$$\text{But area} = 211{,}600 \text{ C. M.}$$
$$\text{Hence } D = \sqrt{211{,}600}$$
$$= 460 \text{ mils}$$
$$1 \text{ mil} = 1/1000 \text{ in.}$$
$$\text{Then } 460 \text{ mils} = \frac{460}{1000} = 0.46 \text{ in.}$$

124. Gage Numbers.—In the United States practically the only gage now used for copper wire is the American Wire Gage commonly called the Brown and Sharpe (B. & S.) gage. This gage was devised in 1857 by Mr. J. R. Brown, one of the founders of the Brown & Sharpe Manufacturing Co. In this gage the size of wire is specified by number. The mathematical law on which this gage is based is, the ratio of any diameter to the next smaller is a constant number.

For practical purposes tables are prepared giving the gage number, diameter in mils or inches, cross-sectional area in circular mils, and other data that may be useful, depending upon the completeness of the table. The numbers usually range from 0000 to 40. The diameter of No. 0000 is 460 mils and of No. 40, 3.145 mils. The student will thus see that the larger the gage number the smaller the diameter. A wire table for ordinary practical calculations is given on page 131. This table was prepared by the Bureau of Standards and is published in circular No. 31 together with others of greater accuracy and detail.

125. Theory.—With this brief description of methods of measuring copper wire we shall be enabled to get a relation between current flowing and the size of the wire by means of the data of experiment 28. Coil No. 3 has a diameter of 10.03 mils and a cross-sectional area of 100.5 C. M. Wire of coil No. 4 has a diameter of 5 mils and a cross-sectional area of 25 C. M. That is, wire of coil 3 is just about four times as large as that of coil 4. Which coil carries the larger current, and what is the ratio of the two currents? Does the current strength have any relation to the size of the wire when the lengths are kept constant?

Since we have defined resistance as that property of a conductor which opposes the flow of current, we see that as the larger wire carries more current than the smaller, it must offer less resistance to the flow of current. The experiment also shows that the current increases directly with the size. That is, coil No. 3 is made of wire four times as large as that of coil 4, and under the same conditions carries four times as large a current. Since the current increases with the size of the wire, the resistance must decrease as the cross-sectional area increases. Furthermore, the area increases as the square of the diameter, and hence the resistance must decrease as the square of the diameter increases, or, as it is usually expressed, the resistance varies inversely as the cross-sectional area, or as the square of the diameter. The student will see that this is also analogous to the resistance offered by water pipes to the flow of water.

TABLE VII.—WORKING TABLE, STANDARD ANNEALED COPPER WIRE

English Units

American Wire Gage (B. & S.)

Gage No.	Diameter in mils	Cross-section, Circular mils	Cross-section, Square in.	Ohms per 1,000 ft. 25° C. (=77° F.)	Ohms per 1,000 ft. 65° C. (=149° F.)	Pounds per 1000 ft.
0000	460.0	212000.0	0.166	0.0500	0.0577	641.0
000	410.0	168000.0	0.132	0.0630	0.0728	508.0
00	365.0	133000.0	0.105	0.0795	0.0918	403.0
0	325.0	106000.0	0.0829	0.100	0.116	319.0
1	289.0	83700.0	0.0657	0.126	0.146	253.0
2	258.0	66400.0	0.0521	0.159	0.184	201.0
3	229.0	52600.0	0.0413	0.201	0.232	159.0
4	204.0	41700.0	0.0328	0.253	0.293	126.0
5	182.0	33100.0	0.0260	0.320	0.369	100.0
6	162.0	26300.0	0.0206	0.403	0.465	79.5
7	144.0	20800.0	0.0164	0.508	0.587	63.0
8	128.0	16500.0	0.0130	0.641	0.740	50.0
9	114.0	13100.0	0.0103	0.808	0.933	39.6
10	102.0	10400.0	0.00815	1.02	1.18	31.4
11	91.0	8230.0	0.00647	1.28	1.48	24.9
12	81.0	6530.0	0.00513	1.62	1.87	19.8
13	72.0	5180.0	0.00407	2.04	2.36	15.7
14	64.0	4110.0	0.00323	2.58	2.97	12.4

TABLE VII.—WORKING TABLE, STANDARD ANNEALED COPPER WIRE.—*Continued*

English Units
American Wire Gage (B. & S.)

Gage No.	Diameter in mils	Cross-section		Ohms per 1,000 ft.		Pounds per 1000 ft.
		Circular mils	Square in.	25° C. (=77° F.)	65° C. (=149° F.)	
15	57.0	3260.0	0.00256	3.25	3.75	9.86
16	51.0	2580.0	0.00203	4.09	4.73	7.82
17	45.0	2050.0	0.00161	5.16	5.96	6.20
18	40.0	1620.0	0.00128	6.51	7.52	4.92
19	36.0	1290.0	0.00101	8.21	9.48	3.90
20	32.0	1020.0	0.000802	10.4	12.0	3.09
21	28.5	810.0	0.000636	13.1	15.1	2.45
22	25.3	642.0	0.000505	16.5	19.0	1.94
23	22.6	509.0	0.000400	20.8	24.0	1.54
24	20.1	404.0	0.000317	26.2	30.2	1.22
25	17.9	320.0	0.000252	33.0	38.1	0.970
26	15.9	254.0	0.000200	41.6	48.1	0.769
27	14.2	202.0	0.000158	52.5	60.6	0.610
28	12.6	160.0	0.000126	66.2	76.4	0.484
29	11.3	127.0	0.0000995	83.5	96.4	0.384
30	10.0	101.0	0.0000789	105.0	122.0	0.304
31	8.9	79.7	0.0000626	133.0	153.0	0.241
32	8.0	63.2	0.0000496	167.0	193.0	0.191
33	7.1	50.1	0.0000394	211.0	244.0	0.152
34	6.3	39.8	0.0000312	266.0	307.0	0.120
35	5.6	31.5	0.0000248	336.0	387.0	0.0954
36	5.0	25.0	0.0000196	423.0	489.0	0.0757
37	4.5	19.8	0.0000156	533.0	616.0	0.0600
38	4.0	15.7	0.0000123	673.0	777.0	0.0476
39	3.5	12.5	0.0000098	848.0	980.0	0.0377
40	3.1	9.9	0.0000078	1070.0	1240.0	0.0299

Note 1.—The values given in the table are only for annealed copper of the standard resistivity. The user of the table must apply the proper correction for copper of any other resistivity. Hard-drawn copper may be taken as about 2.7 per cent. higher resistivity than annealed copper.

Note 2.—Ohms per mile, or pounds per mile, may be obtained by multiplying the respective values above by 5.28.

EXAMPLES

1. **What is the relative resistance of two wires each 100 ft. long, one having a diameter of 20.1 mils and the other a diameter of 5 mils?**

   Solution.—Since the two wires are of equal lengths their resistances will vary only with the square of their diameters. It has just been shown that the larger wire has the smaller resistance. Then the wire whose diameter is 20.1 mils will have the smaller resistance, and the ratio of the two resistances will be $\overline{20.1^2} \div \overline{5^2} = 404.01 \div 25 = 16.1$. Thus the smaller wire has a resistance 16.1 times as great as the larger wire.

2. **How many times as long must the larger wire of problem 1 be in order that the resistances may be equal?**

   Solution.—Since equal lengths of the two wires have resistances whose ratio is 1 to 16.1, and as the resistance of a wire increases directly with the length, the larger wire must be 16.1 times as long.

126. The Effect of Material upon the Resistance of Wire.—In discussing the water-pipe analogy it was stated that the resistance offered by a pipe also depended upon the material of which it is made. To determine whether wires of same lengths and diameters, but of different materials, have different electrical resistances the student must try the following experiment.

127. Experiment 29. To Study Dependence of the Resistance of a Conductor on the Material of Which it is Made.

Apparatus.—Same as in experiment 28.

Operation.—Connect two dry cells, switch, volt-ammeter, and resistance board in series. Remove the proper plugs from the resistance board so that the current must pass through coil 2. Close the switch and read the current. Take five readings as in the preceding experiments, and obtain the mean value of the current. Is the current as large as when two cells were connected in series with coil 3? In order that the data may be obtained under like conditions, that is, pressures being the same, determine what current the two cells in series will send through coil 3. If data obtained at different times are compared, they may be found to vary considerably. This may be due to the fact that both the pressure and internal resistance of the cells may have changed in the meantime. Remember that the current must be permitted to flow through coil 3 for only an instant. Divide the numerical value of the current through coil 3 by the value of the current through coil 2. What is the ratio? Which offers the higher resistance, coil 3 or coil 2?

128. Theory.—The wire of coil 2 has exactly the same length and diameter as that of coil 3; the only difference in the coils is the material of which they are made. The wire on spool 3 is of copper and on spool 2 of German silver. German silver is an alloy of copper, zinc, and nickel. The exact ratio in which these metals are combined cannot be given, but undoubtedly there is more copper than of either of the other two metals.

The results of this experiment show that the material of which a conductor is made determines the current that a given pressure will send through a wire of given cross-section and length. The resistance thus also depends upon the material. This also is clearly analogous to the cases of water pipes.

129. Unit of Resistance.—In order to be able to measure, or compare resistances, some unit of resistance must be chosen. The practical unit is called the *ohm*. The *ohm* is the resistance offered to the flow of an unvarying electric current by a column of mercury 106.3 cm. long, 14.4521 grm. mass, and of constant cross-sectional area, at the temperature of melting ice. This is a definite unit and other resistances are expressed in terms of it.

130. Calculation of Resistance.—We have seen that the cross-sectional area of electrical conductors is measured in circular mils and the length in feet. We can thus consider a piece of wire 1 ft. long, 1 mil (0.001 in.) in diameter as a unit of conductor. The resistance in ohms per foot of annealed copper wire 1 mil in diameter is 9.61 ohms at 0 degrees cent. = 32 degrees Fahrenheit, or 10.371 ohms at 20 degrees cent. This resistance is sometimes called "specific resistance." A better name is *resistivity*.

As we have seen, the resistance of wire of uniform cross-section increases directly with the length (results of experiment 27). Ten feet of annealed copper wire 1 mil in diameter will have a resistance of ten times 9.61 or 96.1 ohms. If l is the length in feet, the resistance of l feet of the same wire will be $9.61 \times l$.

Again the results of experiment 28 show that the resistance decreases directly as the cross-sectional area of the wire increases. Thus if we take a wire whose diameter is 2 mils, its cross-sectional area will be $2^2 = 2 \times 2 = 4$ C. M. and its resistance will be 1/4 of $9.61 = 2.4$ ohms. In general, if 1 ft. of copper wire has a cross-sectional area of A circular mils, its resistance

will be $\frac{9.61}{A}$ ohms. We have just seen, however, that a wire l feet long will have a resistance l times as large. We can thus say that the resistance of copper wire at a temperature of 0 degrees cent. is given by

$$R=\frac{9.61\ l}{A}\text{ ohms}$$

where l is in feet and A in circular mils.

EXAMPLES

1. What will be the resistance of 2,500 ft. of No. 12 copper wire?

Solution.—No. 12 wire has a cross-sectional area of 6,530 C. M. The resistance in ohms at 0 degrees cent. is

$$R=\frac{9.61\times 2500}{6530}$$
$$R=3.7\text{ ohms}$$

2. In wiring a house 3,500 ft. of wire 0.064 in. in diameter is used. What is the resistance of this wire at 20 degrees cent.?

Solution.—According to the formula

$$R=\frac{10.371\times l}{A}$$
$$l=3{,}500\text{ ft.}$$
$$A=64^2=64\times 64=4{,}096\text{ C. M.}$$
$$\text{Hence } R=\frac{10.371\times 3500}{4096}=8.8\text{ ohms}$$

3. How long must a German silver wire be to have a resistance of 40 ohms if it is 81 mils in diameter and if the resistivity of German silver is 125.7 ohms?

Solution.—The formula for the resistance of German silver wire is

$$R=\frac{125.7\,l}{A}$$

Solving this for l we get

$$l=\frac{A\times R}{125.7}$$
$$R=40\text{ ohms}$$
$$A=81\times 81=6{,}561\text{ C. M.}$$
$$\text{Hence } l=\frac{40\times 6561}{125.7}$$
$$l=209\text{ ft., nearly}$$

131. Resistivity or Specific Resistance.—In the foregoing discussion the resistance of 1 ft. of annealed copper wire 1 mil in diameter was stated to be 9.61 ohms at 0 degrees cent. This quantity is called *resistivity* or *specific resistance* as it depends

upon the material of which the conductor is made. Thus when we desired to find the resistance of German silver, 125.7 was used for the resistivity. This is because a German silver wire of the same length and size as a copper wire will have a resistance about 13.2 times as high.

The resistivity of metals will depend upon their purity and temperature. The resistivity of alloys such as German silver will depend upon the composition of the alloys. The resistivity of some of the most common metals is given in Table VIII.

TABLE VIII.—RESISTIVITY OF METALLIC WIRES

Substance	Resistance in ohms at 0 degrees cent. of a wire 1 ft. long 1 mil in diameter
Aluminum, annealed	15.8
Antimony, pressed	213.1
Bismuth, pressed	787.5
Copper, annealed	9.61
Copper, hard drawn	9.86
Gold, annealed	12.56
Gold, hard drawn	12.78
Gold-silver, 2 parts gold 1 part silver, by weight.	65.21
German silver	125.7
Iron	58.31
Lead	115.1
Mercury	565.9
Nickel	74.78
Platinum	54.35
Silver, annealed	8.781
Silver, hard drawn	9.538

132. Change of Resistance with Temperature.—The student will notice that the definition of the ohm specifies that the temperature must be that of melting ice, that is, 0 degrees cent. Likewise the resistivities given in the above table are correct only when the temperature is 0 degrees cent. The question naturally arises, how does the resistance change with temperature?

133. Experiment 30. To Study Effect of Temperature upon Resistance.

Apparatus.—Same as in experiment 29.

Operation.—Connect three dry cells in series with the voltammeter and resistance board exactly as in experiment 29 except that the current is to pass through coil 1 in place of coil 2. Take a watch or some other convenient timepiecee and place it where

you can observe the time. Having adjusted the apparatus carefully, press down the push-button on the volt-ammeter and close the switch. Observe carefully the value of the current just as soon as the pointer comes to rest. Leave the switch closed for about 20 seconds, one-third of a minute. Under no circumstances must the switch be closed longer than half a minute. Just before opening the switch read the ammeter and note if the current has increased or decreased. Feel of the coil and notice if it is warm. If the switch should be left closed too long the coil may become hot enough to burn off the insulation, hence, the necessity of observing the time.

After the coil has become cool, repeat until you are certain that the current decreases. The decrease in the current will not be great but should be noticeable.

134. Theory.—Coil No. 1 is of copper wire 600 cm. long and offers considerable resistance to the flow of the current. The current that passes through it when three cells are connected in series is not over one-half an ampere at the start. This current, however, slowly decreases if the circuit is left closed for a brief time. There can be only two causes for this, either the pressure of the dry cells has changed, or the resistance of the coil has changed. That the change in current is not due to a change in the pressure of the cells can be shown easily by measuring the pressure before and after the experiment. (See page 93.)

If the pressure is measured it will be seen that the voltage shows no appreciable change. The change in current must then be due to a change in resistance. The current decreases, and therefore the resistance must increase. The student observed that the coil became quite warm, and hence its temperature must have been quite high. In short, then, we can say that the resistance of copper increases as the temperature increases. If measurements were made on other metals the same relation would be found to hold.

The resistance of pure metals increases with the rise in temperature. For purposes of calculation the change in the resistance of 1 ohm for a change of 1 degree cent. in temperature has been carefully measured by the Bureau of Standards and for this change is approximately the same for each metal. Its numerical value for annealed copper is about 0.00393. Thus the change in the resistance of the wire on coil 1 is approximately 0.393 of 1 per cent for every centigrade degree change in tempera-

ture. If the coil has a resistance of 10 ohms at 0 degrees cent. its resistance at 100 degrees cent. will be

$$10+10\times0.00393\times100=13.93 \text{ ohms.}$$

These principles can be formulated thus: If R_o is the resistance of a wire at 0 degrees cent. its resistance R_t at t degrees cent. will be equal to R_o plus the increase. This increase, as has been shown, is .00393 ohm for every ohm for 1 degree; hence the increase in R_o ohms for 1 degree change in temperature will be 0.00393 R_o, and for t degrees it will be 0.00393 R_o t. The total, or R_t, resistance is then

$$\begin{aligned} R_t &= R_o+0.00393\ R_o\ t \\ &= R_o\ (1+0.00393\ t) \end{aligned}$$

EXAMPLE

A copper coil has a resistance of 200 ohms at 0 degrees cent. What is its resistance at 100 degrees cent.?

Solution.—

$$\begin{aligned} Ro &= 200 \text{ ohms} \\ t &= 100 \\ R_t & \text{ is required} \\ R_t &= 200(1+0.00393\times100) \\ &= 200(1+0.393)=278.6 \text{ ohms} \end{aligned}$$

135. Practical Applications.—This example shows that the change in resistance due to a change in temperature must be taken into consideration in the design of electrical apparatus, and also in many electric problems.

Any one who has had experience with generators knows that if the field current is adjusted while the field winding is cold, in a short time further adjustment may be necessary. The reason for this is very evident. The current through the field is determined by the rheostat resistance and field resistance. When the current is first adjusted to give full voltage the resistances of rheostat and field winding are lower than after the current has been flowing through them for a short time. The current heats the wire, increasing its resistance as explained, and, as the resistance increases, the current must decrease, thus necessitating further adjustment.

In using a voltmeter to measure the voltage of a circuit it is advisable to keep its circuit closed only while the reading is being taken. If the circuit is kept closed for some time the

windings of the voltmeter will increase in temperature and consequently a smaller current will flow through the instrument. Since the deflection of the instrument depends upon the current flowing through it, the deflection will be in error.

Somewhat the same thing is true of watthour meters. If a watthour meter is tested immediately upon being connected to the circuit and again after having been in service for an hour, it will be found that it no longer registers the same. One reason for this is that the voltage coil has changed its resistance by being heated by the pressure current. It is thus necessary to leave the meter in circuit for some time before testing in order that the pressure coil may reach a constant temperature.

Another most important practical application of this principle is the measurement of high temperatures. For this purpose, platinum wire is used. The wire is wound upon a mica frame and incased in a porcelain tube as shown in Fig. 89. To measure

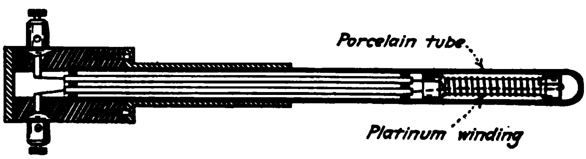

Fig. 89.

the temperature in an annealing oven, for instance, the resistance of the platinum wire is determined at zero cent. temperature, and then again at the temperature of the oven. The temperature is then obtained by dividing the difference in the resistance by the resistance at zero degrees times the resistance temperature coefficient of platinum. By such means temperatures as high as 1200 degrees cent. can be quite accurately measured. The principle can be illustrated by an example.

EXAMPLE

The resistance of the armature of a certain motor at 0 degrees cent. is 1.7 ohms. After a run of a few hours the resistance is again measured and is found to be 1.98 ohms. What is the temperature of the winding?

Solution.—The change in resistance is $1.98-1.7=0.28$ ohms. The change in resistance for 1 ohm for 1 degree cent. is 0.00393 ohm; for 1.7 ohms it is $.00393\times1.7=0.006681$ ohm. Since the total change is 0.28 ohms the change in temperature will be approximately

$$\frac{0.28}{.006681}=42 \text{ degrees cent.}$$

136. Temperature Coefficient of Resistance.—The change in the resistance of 1 ohm for a change of 1 degree in temperature, discussed in the foregoing, is called the *resistance temperature coefficient.* For commercial copper wire the American Institute of Electrical Engineers has adopted the value 0.00393. As already pointed out, this is approximately the resistance temperature coefficient for most pure metals, except the magnetic metals. For iron the temperature coefficient is 0.00625 per degree cent.

An alloy has a much lower temperature coefficient, and to a large extent its value depends upon the metals that are combined and also upon their ratio of combination. The temperature coefficient of German silver may be considered to be approximately one-tenth as large as that of copper. An alloy

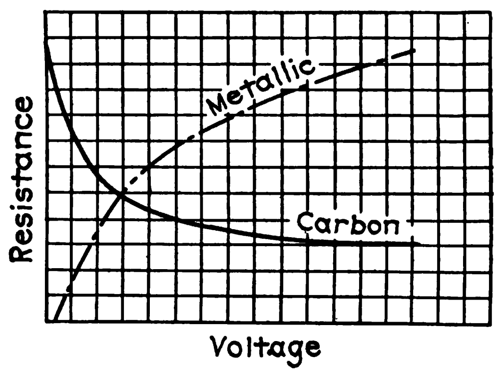

FIG. 90.

consisting of 84 per cent copper, 12 per cent manganese, and 4 per cent nickel, has, at ordinary temperatures, a very small temperature coefficient, which at higher temperatures becomes zero, and finally negative; that is, the resistance finally decreases with increases of temperature. This alloy called manganin is used almost exclusively in standard resistances and also in electrical measuring instruments.

Many substances have a negative temperature coefficient. That is, their resistance decreases as the temperature increases. Carbon, of which the filament of the carbon incandescent lamp is made, is one of these substances. The resistance temperature coefficient of the material of the metallic filament, such as tungsten lamps, is positive. The change in resistance with voltage of these two kinds of filaments is shown in Fig. 90.

The resistance of all electrolytes decreases with rise of temperature, and the same thing is true of substances commonly called insulators.

137. Resistance of Contacts.—When two conductors are joined and an electric current is passed through the junction, a drop of voltage will result. The laws of this contact drop have recently been investigated by Mr. F. W. Harris, who states the results of his investigations in the form of four laws:[1]

1. All other conditions being constant, the voltage across a contact joint will increase directly with the current.

2. Where the conditions of the surface in contact are not affected thereby, the voltage across a contact will vary inversely with the pressure.

3. The resistance between materials depends directly upon the resistivity of the materials, those having a low resistivity having also a low contact resistance.

4. The resistance between contacts depends not upon their area, but only on the total pressure with which they are forced together.

The results stated in law 1 merely show that the effect of a contact upon current flow is the same as that of a resistance and hence may properly be treated as such.

Law 2 shows that the more closely the surfaces are pressed together, the less the pressure drop across the junction. This shows the necessity of keeping all electrical contacts clean and tight. Many a piece of electrical apparatus has failed to give satisfactory service on account of a loose contact.

At first reading it may seem that law 4, which is new, does not express the facts, for it is common practice, in the design of switches, to limit the current density to 50 or 75 amperes per square inch at the switch contacts. This is done for the purpose of reducing the voltage drop at the contacts to a minimum. According to law 4 the voltage drop across the contacts can be reduced greatly by increasing the pressure between the jaws and the blade of the switch. Practical requirements of construction and operation limit the pressure to which the junctions can be subjected.

RECAPITULATION

1. *Electrical resistance* is the property of a conductor by virtue of which it opposes the passage of electricity through it. At constant temp-

[1] *Electrical Journal*, July, 1913, page 637.

erature the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area.

2. *Resistivity or specific resistance* is the characteristic propriety of a substance upon which the resistance of a conductor formed of this material depends. For purposes of measurement the unit of resistivity is taken as the resistance of a conductor of unit length and unit cross-sectional area. In practical work the unit length is usually 1 ft. and unit cross-section is 1 circular mil. In scientific calculations 1 cm. is taken as the unit length and square centimeter as the unit cross-section.
3. The *mil* is the unit of length used in measuring the diameters of wires. It is equal to 1/1000 in.
4. The *circular mil* is the unit area used in measuring the cross-sectional area of wires. The circular mil is equal to the area of a circle 1 mil in diameter.
5. The *ohm* is the unit of resistance. The ohm is defined as the resistance offered to the flow of an unvarying electric current by a column of mercury 106.3 cm. long, 14.4521 grm. mass, of constant cross-sectional area and at the temperature of melting ice.
6. The resistance of wires at a temperature of 0 degrees cent. may be calculated by the following formula:

$$R=\frac{rl}{A}$$

where r is the resistivity of the material at 0 degrees cent., l the length, and A the cross-sectional area.

7. The resistance of most conductors changes with temperature. The change in one ohm caused by a change of 1 degree cent. is called the *temperature coefficient of resistance.* The temperature coefficient of metals is positive and approximately the same for all pure metals. Non-metals and electrolytes have a negative temperature coefficient.
8. When two surfaces are joined and a current is passed at right angles to the surfaces a loss of voltage will result at the junction. The cause of the voltage drop is called contact resistance. This voltage drop takes place in accordance with the following laws:

(a) All other conditions being constant, the voltage across a contact joint increases directly with the current; or, the joint between two materials behaves exactly like a resistance.

(b) Where the conditions of the surface are not affected thereby, the voltage drop across a contact will vary inversely with the pressure.

(c) The resistance between materials depends directly on the resistivity of the materials; those having a low resistivity also have a low contact resistance.

(d) The resistance between contacts depends not upon their area, but only on the total pressure with which they are forced together.

CHAPTER VIII

FLOW OF CURRENT IN A CIRCUIT

138. Introduction.—So far we have learned that the flow of current through or along a conductor depends upon the electrical pressure applied, and when the pressure is continuous or direct, upon the resistance of the circuit. It has also been shown that the property of a conductor called resistance is determined by the material, length, and cross-sectional area of the conductor. Nothing has so far been said about the exact or numerical relation between current, pressure, and resistance. This relation was first investigated by Dr. G. S. Ohm, in 1827, and is known as Ohm's law.

139. Ohm's Law.—In experiment 29 it was shown that when two cells were connected in series with coils 2 and 3 of the resistance board, successively, the currents through the coils differed greatly, the greater current flowing through coil 3. This was explained by saying that coil 2 offered higher resistance to the passage of the current, or that coil 2 had many times the resistance of coil 3. Since the only quantities that we have measured are electrical pressure and current, the resistance of the circuit may be looked upon as the ratio of the pressure to the current. In algebraic symbols we can write this as follows:

$$R = \frac{E}{I} \text{ or}$$

$$\text{Resistance} = \frac{\text{Electrical Pressure}}{\text{Current}}$$

where R stands for resistance, E for electrical pressure, and I for the current. This expression, or the relation between current, pressure, and resistance, is known the world over as Ohm's law. If the pressure is given in volts and the current in amperes, the resistance R is given in ohms. This expression is of the greatest importance in all electrical calculations, and accordingly we are justified in giving a comparatively extended discussion of it. Ohm's law stated in simple words means that in any circuit the pressure bears a constant relation to the current. It may be

stated another way; for instance, the expression may be written in the form

$$I=\frac{E}{R}$$

which is, perhaps, the most common. This expression means that the current I is equal to the pressure E divided by the resistance R. We can then say that when R is constant, I, the current, will increase or decrease as E, the pressure, increases or decreases. Doubling E will double the current, etc. Again if the pressure E remains constant, the current I will vary inversely as the resistance R, increasing when R decreases and decreasing when R increases. This relation can be easily verified by a simple experiment as follows:

140. Experiment 31. To Verify Ohm's Law.

Apparatus.—
Three dry cells
Volt-ammeter
Resistance board
Switch
Connecting wires

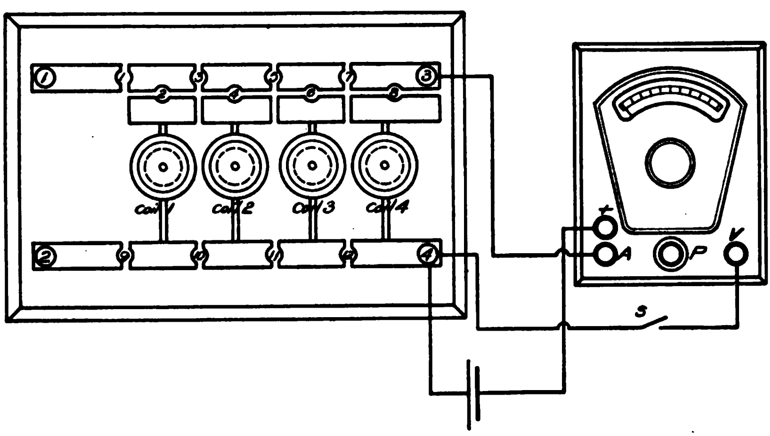

FIG. 91.

Operation.—First connect one fresh dry cell as indicated in Fig. 91. Leave switch S open at first, and remove plugs 12, 11, and 8. Press down on pearl push-button P and insert plug 12. This connection will give current through coil 3. Read and record this current. Now release the push-button and close switch S.

This will give the voltage applied to coil 3. Read and record this voltage, also.

Next connect two dry cells in series in place of the one cell. Again measure the current through coil 3 and the voltage as before. It will be well to take three or four readings of current and also three or four readings of the voltage in order that an average value may be obtained.

Always remove plug 12 as soon as a reading is made. This breaks the current circuit and avoids heating the coil. Compare the currents and voltages in the two sets of readings. When two cells are used, how does the voltage compare with the voltage when one cell is used? Has the current increased as the pressure? Next insert plug 8, remove plug 9, and repeat the experiment. This connection will send the current through coil 4. Record the values of current and pressure.

The resistance of coil 3 is about 1 ohm and that of coil 4 is about 4 ohms. In each case divide the voltage by the resistance and see if the current is approximately given by

$$I=\frac{E}{R}$$

141. Theory.—As the preceding experiment shows, the current strength is directly proportional to the pressure applied. It is possible to make a perfectly general statement of this law. Thus in general one may say that the current strength in any circuit is directly proportional to the sum of all the electromotive forces in the circuit. This relation expressed algebraically is

$$E=KI$$

or

$$\frac{E}{I}=K, \text{ a constant}$$

This holds for both direct and alternating-current circuits so long as the physical conditions surrounding the circuit remain unchanged. For direct-current circuits K is equal to what is called the resistance of the circuit and under these conditions

$$E=RI$$

or

$$\frac{E}{I}=R$$

Thus the ratio of the electromotive force to current is constant so long as physical conditions remain constant. If, for instance, the temperature changes, this ratio will change. This is explained by saying that the resistance changes.

In alternating-current circuits the total e.m.f. must include the e.m.f.'s of mutual induction, self induction, and capacity. When these are considered Ohm's law, as stated, still holds.

In applying Ohm's law to the solution of electrical problems, all or the algebraic sum of all of the pressures that may be included as well as all of the resistances, must be considered. The student will readily understand this if he will perform experiment 31 in a little different way. First measure the electromotive force of one cell as shown in Fig. 63. Divide this pressure by 1 ohm and compare the result with the current through coil 3 which was obtained in the first part of the experiment. The result is considerably larger than the current measured. This is due to the fact that the connecting wires and cell have some resistance which is not considered. An examination of the circuit will show that the current flows from the zinc plate, or cup, of one cell through the electrolyte to the carbon rod in the center; then through the connecting wire to the next cell, through its electrolyte, through the binding screws and connecting wires to the ammeter; then through wires connecting ammeter and resistance board, through resistance coil and back to the cell. If, in such a case, we know the value of the separate pressures and resistances that are in series, we can calculate the current by dividing the sum of the pressures by the sum of the resistances.

EXAMPLES

1. Let there be 5 cells in series, each having a pressure of 1.4 volts and an internal resistance of 0.5 ohm. If the resistance of the connecting wires is 1.5 ohms, what current will flow through a coil of 5 ohms resistance?

   Solution.—The total pressure is equal to $5 \times 1.4 = 7$ volts. The total internal resistance of the cells is $0.5 \times 5 = 2.5$ ohms. The resistance of the circuit is then

   $$R = 1.5 + 2.5 + 5 = 9 \text{ ohms}$$

   The current is given by

   $$I = \frac{E}{R} = 7/9 \text{ ampere}$$

2. The counter pressure of a lead storage cell is 2.3 volts; its internal resistance is 0.05 ohm. How much current will 4 dry cells send through the storage cell if each dry cell has an internal resistance of 1 ohm, polarization to be neglected?

Solution.—The voltage of the 4 cells in series is

$$4 \times 1.4 = 5.6 \text{ volts}$$

The resultant pressure is the difference between this voltage and the counter pressure of the storage cell; this is

$$5.6 - 2.3 = 3.3 \text{ volts}$$

The total resistance is

$$4 \times 1 + 0.05 = 4.05 \text{ ohms}$$

The current is then

$$3.3 \div 4.05 = 0.8 \text{ ampere}$$

It is very evident that by means of Ohm's law any one of the three quantities I, E, and R can be determined, provided the other two are known. Thus, in experiment 31, the pressure E was measured, and R was given. The value of the resistance of coil 2, or any other coil on the board can be determined by measuring the pressure applied, and then connecting the apparatus as in Fig. 91 and measuring the current. The resistance of the coil is then equal to $R = \frac{E}{I}$ ohms, or pressure divided by resistance. In this case R, of course, includes the resistance of the connecting wires.

EXAMPLES

1. What is the resistance of a 60-watt carbon incandescent lamp when a 110-volt pressure gives a current of 0.55 amperes?

Solution.—

$$R = \frac{E}{I}$$
$$E = 110 \text{ volts}$$
$$I = 0.55 \text{ ampere}$$
$$R = \frac{110}{0.55} = 200 \text{ ohms}$$

2. A storage battery whose e.m.f. is 24 volts and internal resistance 0.6 ohm is connected to a wire whose resistance is 5 ohms; what is the current? What is the voltage between the ends of the wire?

Solution.—

$$E = 24 \text{ volts}$$
$$R = 0.6 + 5 = 5.6 \text{ ohms}$$

Then $I = \frac{E}{R}$

$$= \frac{24}{5.6} = 4.3 \text{ amperes (nearly)}$$

From Ohm's law we also have

$$E = R \times I$$

That is, the pressure drop along a resistance is equal to the resistance times the current. The wire resistance is 5 ohms and current is 4.3 amperes; hence, the voltage between wire ends is $5 \times 4.3 = 21.5$ volts.

3. A battery whose e.m.f. is 8 volts delivers 2 amperes to a circuit of 3.6 ohms resistance. What is the internal resistance of the cell?

Solution.—The pressure drop across resistance is $3.6 \times 2 = 7.2$ volts. The battery drop must be $8 - 7.2 = 0.8$ volts, and the battery resistance by Ohm's law must be $0.8 \div 2 = 0.4$ ohm.

4. The open circuit voltage of a storage battery is 11 volts. This battery will send a current of 4 amperes through a coil at a pressure of 10 volts. What is the battery resistance?

Solution.—The voltage spent in forcing the current through the battery is

$$11 - 10 = 1 \text{ volt}$$

then
$$R = \frac{E}{I} = 1/4$$
$$R = 0.25 \text{ ohms}$$

142. Capacity.—In Article 141 it was stated that in alternating current circuits the total e.m.f. must include the e.m.f.'s of mutual induction, self induction, and capacity. The effect of mutual induction and self induction has already been mentioned, but the subject of capacity and its influence has not been explained.

If two metal plates be separated by a good insulator, and the two plates be connected to a source of electrical pressure, a momentary current will flow into the plates which will become positively and negatively charged. The intensity of the momentary current will depend upon the ability of the plates to hold a charge of electricity. This ability of a conductor or a system of conductors, to store electricity is called electrical capacity. A system of conductors arranged as indicated in Fig. 92, is called a condenser. The capacity of a condenser is determined by the arrangement, number, and size of the conducting plates as well as the thickness and material of the dielectric. The quantity of electricity that a condenser will hold is determined by the capacity of the condenser and by the pressure applied.

A better understanding of the action of a condenser may be had by considering an analogy. Suppose we have an air tank that under one atmospheric pressure holds a certain definite quantity of air, say 5 lb. We can define the capacity of the vessel in terms of the number of pounds of air it holds, and call it a 5-lb. tank.

If the pressure is doubled, the tank will hold 10 lb. of air. Since we have defined the capacity of the tank in terms of unit (one atmosphere) pressure, we cannot call it a 10-lb. tank. A 10-lb. tank under the same conditions will hold 20 lb. of air.

Furthermore, suppose the tank to be exhausted; evidently no back pressure will be exerted when air is first admitted to the tank. As soon as some air is admitted to the tank, back pressure begins to manifest itself, and when the back pressure equals the applied pressure, no more air enters the tank. We thus see that the amount of air entering per unit time depends upon the back pressure, and this back pressure will depend upon the capacity of the tank. For instance, if we put 5 lb. of air in a 10-lb. tank, the back pressure will be one-half as great as when 5 lb. of air are put into a 5-lb. tank. We can then say that unit capacity of a tank is such that when 1 lb. of air is forced into it the pressure will be equal to one atmosphere. Evidently a certain amount of work will be done in forcing the air into the tank, and we could define unit capacity in terms of the work expended.

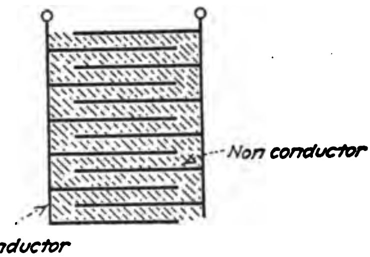

Fig. 92.

The capacity of electrical conductors is analogous to the capacity of the air tank discussed above. The capacity of a condenser or system of conductors is usually defined in terms of the quantity of electricity required to raise the difference of pressure between the terminals by one volt. In accordance with this definition the quantity of electricity that a condenser will contain is equal to the product of the capacity and pressure.

In so far as determining current flow is concerned, the effect of capacity in direct-current circuits is either negligible or it serves as an open circuit. It is, however, of considerable importance in determining the flow of alternating currents.

143. Resistances in Series.—When resistances are connected end to end, so that the total current must flow through all of the resistances, we say that they are connected in series. The total resistance of several resistances so connected is equal to the sum of their resistances. This is almost self evident and can be

easily understood by referring to experiment 27, where it was shown that the resistance offered by coils 1 and 4 in series is three times that offered by coil 4 only. Experiment 27, however, is intended to show how the resistance of a conductor varies with length. The same principles hold, however, when two coils of different lengths, cross-sectional areas, and materials are connected in series. To show this, let the student perform the following experiment.

144. Experiment 32. To Study Resistances in Series.

Apparatus.—
Dry cells
Resistance board
Volt-ammeter
Connectors

Operation.—Connect two dry cells, resistance board, and volt-ammeter as in Fig. 91. Adjust the resistance board so that the current must pass through coil 3 only. Determine this current and pressure across the coil just as in experiment 31. Keep the circuit closed for an instant only to prevent the burning out of the coil. Take three separate readings and average them. Calculate the resistance of coil 3 by Ohm's law; viz.,

$$R=\frac{E}{I}$$

Next connect the board so that the current must flow through coil 4 only and measure the pressure and current three times. From the average of the readings calculate the resistance of coil 4 as above. Put three dry cells in place of the two cells and connect coils 3 and 4 in series. To do this the connections shown in Fig. 91 will have to be changed as follows: Transfer the connection from binding post 3 to binding post 1 and also transfer the wires from binding post 4 to binding post 3. Remove plugs 2, 4, and 7. The current will then enter binding post 1, pass through plugs 1, 3, 5, 6, coil 3, plug 12, coil 4, plug 8 and back to circuit through binding post 3. With this connection measure the current through coils 3 and 4. Take three or more readings and calculate the resistance as before. How does this value agree with the sum of the resistances of coils 3 and 4?

Tabulate your results as follows:

Coil	Pressure E	Current I	Resistance $R=\frac{E}{I}$
3			
4			
3 and 4			

EXAMPLES

1. A pressure of 10 volts is connected in series with three resistances of 1, 4 and 5 ohms, respectively. What is the current?

Solution.—The total resistance is

$$R=1+4+5=10 \text{ ohms}$$

then
$$I=\frac{E}{R}=\frac{10}{10}=1 \text{ ampere}$$

2. Four equal resistances are connected in series, and a pressure of 50 volts is applied, when it is found that 5 amperes are flowing. What is the resistance of each coil separately?
Solution.—Total resistance

$$R=\frac{E}{I}=\frac{50}{5}=10 \text{ ohms}$$

Since 10 ohms is the sum of 4 equal resistances, each must equal

1/4 of 10 = 2.5 ohms respectively

3. A shunt generator field has a resistance of 50 ohms. There is connected in series with the field a regulating rheostat whose resistance can be varied from 0 to 40 ohms. What is the possible range of current through the field if the pressure is 110 volts?
Solution.—When rheostat resistance is 0, the current is

$$I_1=\frac{110}{50}=2.2 \text{ amperes}$$

When rheostat is all in, the resistance in series is

$$50+40=90 \text{ ohms}$$

and current is

$$I_2=\frac{110}{90}=1\tfrac{2}{9} \text{ amperes}$$

Hence the current can be varied from $1\frac{2}{9}$ amperes to 2.2 amperes.

145. Voltage Drop.—From the relation $I=\frac{E}{R}$ we can also get $I\times R=E$. That is, when a current is passing through a resist-

ance the fall of pressure, or the voltage drop, is equal to the product of current and resistance. For example, a current of 5 amperes flowing through a coil of 10 ohms resistance gives a pressure drop, or voltage drop, of $5 \times 10 = 50$ volts. This principle has already been used.

146. Experiment 33. To Show That Voltage Drop Equals Product of Current by Resistance.

Apparatus.—Same as in experiment 32.

Operation.—Connect three dry cells, switch, and resistance board in series. Connect one side of the cell circuit to binding post 1 and the other to binding post 4, Fig. 85. Remove plugs 3, 4, and 12. When this is done coils 1, 3, and 4 are in series. Connect two wires to the voltmeter, that is, connect one wire to + and the other to V binding posts, and leave the other two ends of the wires free. Close the switch and press the free end of one wire to the brass block between plugs 1 and 3, and the free end of other wire to the brass block between binding posts 9 and 10. Observe the indication of the voltmeter and record the same. If the pointer deflects in the wrong direction interchange the ends. Next press the free ends of the wires connected to voltmeter on the brass blocks connected to coil 3 and take a reading. Finally press them down upon the brass blocks connected to coil 4. Repeat the readings so as to be certain that no mistake has been made. Open the switch between readings so that the coils will not heat up. Having determined the voltage drop across each coil, connect the cells, switch, board, and ammeter in series, as shown in Fig. 86. The circuit wires must be connected to binding posts 1 and 4 instead of 1 and 2, as shown in Fig. 86. Remove plugs 3, 4, and 12; close the switch and press down the pearl push-button on the ammeter. Read the ammeter, open the switch for an instant, and close it again. Take three readings of the current. Tabulate your results as follows:

Reading	Coil	R Resistance	I Current	$I\times R$	Voltage drop	Difference
1	1					
2	1					
3	1					
1	3					
2	3					
3	3					
1	4					
2	4					
3	4					

In column R write the resistance of the coils as determined in experiments 31 and 32, and in column I write the current flowing through all three coils 1, 3, and 4 in series. In column $I\times R$ write the products obtained by multiplying the current in the coil by its resistance, and in the column marked voltage drop, write the separate voltmeter readings obtained when voltmeter terminals were connected to, or pressed upon, the brass blocks connected to coils 1, 3, and 4 respectively. How do the products $I\times R$ compare with the measured voltage drop?

147. Theory.—The subject of voltage drop is extremely important in all wiring calculations and power transmission problems. For instance, suppose current is sent over a long transmission line, much, or several per cent, of the voltage will be necessary to overcome the resistance of the line. Suppose a line of No. 00 wire is 5 miles long and 20 amperes are flowing. The voltage loss or drop is equal to 20 times the resistance of 10 miles of No. 00 wire. No. 00 wire has a resistance of 0.0795 ohms per 1,000 ft. at a temperature of 68° F. See Table VII. Ten miles is equal to $10\times5{,}280$ ft. The resistance of this length of wire is $52.8\times0.0795=4.2$ ohms. The voltage drop due to 20 amperes is $4.2\times20=84$ volts.

In house wiring, if the resistance of the wires is too high, the voltage drop to the lamps will be excessive and the lamps will burn dimly. The light-producing power of a lamp decreases rapidly with decrease of the applied voltage. A decrease of 5 per cent in the voltage may cause a decrease of 25 per cent in the light.

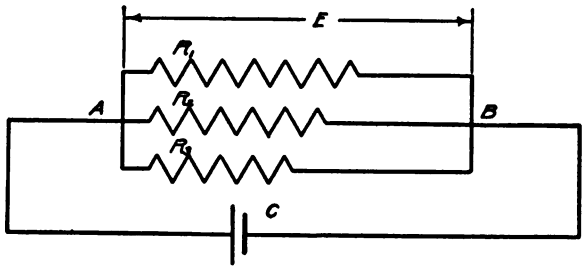

FIG. 93.

148. Resistances in Parallel.—The next question we shall investigate is the relation between current, pressure, and resistance, when several conductors are connected in parallel, that is, connected as indicated in Fig. 93, where R_1 and R_2 represent the several resistances. The student will readily see that in a circuit represented by Fig. 93a the current divides at the point A, part going through R_1, part through R_2. The two parts of

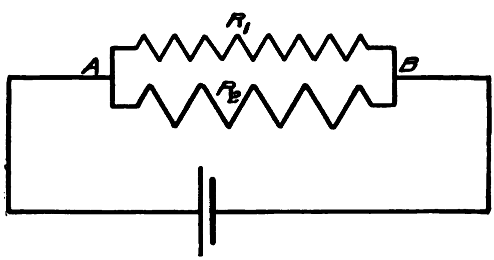

FIG. 93a.

the current combine again at B from which they flow as one current. The problem that we are to solve is then to determine the total current that will flow through this circuit if we know the numerical values of R_1, R_2, and the pressure of the cell.

It is very evident that if we neglect the internal resistance of the cell and the resistance of the wires connecting cell C with

points A and B, the difference of pressure between points A and B is the pressure of the cell. This being the case, the current in each conductor is given by Ohm's law. Thus if I_1 and I_2 are the currents in branches R_1 and R_2, the currents are given by

$$I_1 = \frac{E}{R_1}$$

and

$$I_2 = \frac{E}{R_2}$$

and the total current must be the sum of these currents. That is,

$$I = I_1 + I_2 = \frac{E}{R_1} + \frac{E}{R_2}$$

EXAMPLES

1. Two conductors whose resistances are 2 and 3 ohms respectively are connected in parallel to a 12-volt pressure. What is the total current? What is the joint resistance?

   Solution.—According to what has just been said, the currents through the separate resistances are

$$I_1 = \frac{E}{R_1} = \frac{12}{2} = 6 \text{ amperes}$$

and

$$I_2 = \frac{E}{R_2} = \frac{12}{3} = 4 \text{ amperes}$$

   The total current is then

$$I_1 + I_2 = 6 + 4 = 10 \text{ amperes}$$

   We have defined the resistance as the ratio of the pressure to the current, and accordingly in the example, when 12 volts are applied, and amperes flow through the circuit, the resistance must be

$$R = \frac{E}{I} = \frac{12}{10} = 1.2 \text{ ohms}$$

   This plainly is a quantity that differs from either 2 or 3 or their sum, 5.

2. Two incandescent lamps are connected in parallel across a 110-volt circuit. One lamp has a resistance of 220 ohms and the other only 110 ohms. What is the total current, and what is the joint resistance?

   Solution.—

$$I_1 = \frac{110}{220} = 0.5 \text{ ampere}$$

$$I_2 = \frac{110}{110} = 1 \text{ ampere}$$

Total current $I = 0.5 + 1 = 1.5$ amperes

$R = 110 \div 1.5 = 73.67$ ohms

149. Experiment 34. To Study the Resistance of Conductors in Parallel.

Apparatus.—
Volt-ammeter
Two dry cells
Resistance board
Connectors
Switch

Operation.—Connect the two dry cells, volt-ammeter and resistance board as indicated in Fig. 91, measure the resistance of coils 3 and 4 separately according to the directions of experiment 32. Then with plug 11 removed and plugs 6, 7, 8, and 12 inserted, measure the current by pressing down on push-button *P*. Release *P* and close switch *S*. This gives the voltage drop across coils 3 and 4 in parallel. Calculate the resistance by Ohm's law. How does the current through both coils compare with the sum of the currents through the separate coils?

150. Theory.—The foregoing experiment shows clearly that when two resistances are connected in parallel, the total current is equal to the sum of the currents in each conductor. The student may not be able to get values that show this with mathematical exactness. The reason for this is evident; the resistances of the connecting wires and cells modify this condition to some extent. These external resistances are a greater per cent or part of the joint resistance of spools 1 and 3 than of the resistance of either spool alone. The current in every case is determined by the resistance of cells, connecting wires, and spools. If the resistance of the cells and wires is a greater percentage of the joint resistance than of the resistance of either spool, the current through the spools in parallel must be somewhat less than the sum of the currents obtained when the spools are connected to the cells separately. This external resistance is so small that the values are close enough for practical purposes.

A water pipe analogy may help to make the foregoing principles clear. If two equal pipes are connected side by side, each will carry the same water current and the total current is the sum of the currents in the two pipes. Also this total current is two times the current carried by one pipe when the pipes are exactly alike in every respect. The same principle holds in electrical conductors. The current through two conductors of equal resistances in parallel is two times the current in one conductor,

and accordingly the resistance must be equal to half of that offered by one conductor. This can be looked upon from still another viewpoint. When two conductors of the same size are connected in parallel, the cross-sectional area of the two conductors is evidently equal to twice that of one. Then if the resistance of one is given by

$$R_1=\frac{rl}{A} \text{ (see page 135)}$$

the resistance of two in parallel will be given by

$$R_2=\frac{rl}{2A},$$

since the only quantity that has been changed is A, the cross-sectional area. $R_1 \div R_2$ is thus

$$\frac{R_1}{R_2}=\frac{\frac{rl}{A}}{\frac{rl}{2A}}=2$$

That is, the resistance of one is twice the joint resistance of the two conductors in parallel.

151. Calculation of Joint Resistance.—When the wires are connected in parallel the joint resistance can be determined experimentally as in the foregoing experiment. The facilities for thus determining the resistance are not always available; hence, in most instances it is preferable to calculate the joint resistance. This can be done readily when the principles are understood.

It has been shown that when two resistances, R_1 and R_2, are connected in parallel to a pressure E, the total current is given by

$$I=\frac{E}{R_1}+\frac{E}{R_2}$$

$$I=E\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

This means that I, the total current, is equal to E, the pressure, multiplied by the sum of the reciprocals of the two resistances. (The reciprocal of any number is one divided by the number.)

If R is the joint resistance, the current by Ohm's law is given by

$$I=\frac{E}{R}$$

Then $\frac{E}{R}$ must equal $E\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$

$$\text{or } \frac{E}{R}=\mathrm{E}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$$

Cancelling the E's, we get

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}$$

$$\text{or } \frac{1}{R}=\frac{R_2+R_1}{R_1\times R_2}$$

Taking the reciprocal of both sides of the equation, this becomes

$$\frac{1}{\frac{1}{R}}=\frac{1}{\frac{R_2+R_1}{R_1\times R_2}}$$

$$\text{or } R=\frac{R_1\times R_2}{R_1+R_2}$$

That is, the joint resistance of two resistances in parallel is equal to the product of the resistances divided by their sum.

EXAMPLE

Two wires whose resistances are 2 and 3 ohms are joined in parallel. What is the joint resistance?

Solution.—Joint resistance is given by

$$R=\frac{R_1\times R_2}{R_1+R_2}$$

$$R_1=2$$

$$R_2=3$$

$$\text{Then } R=\frac{2\times 3}{2+3}=1.2 \text{ ohms}$$

Compare this value with that obtained in the illustrative example on page 155.

When the two wires are exactly alike, or have equal resistances, $R_1=R_2$ and our formula reduces to

$$R=\frac{R_1\times R_1}{R_1+R_1}=\frac{R_1^2}{2R_1}=\frac{R_1}{2}$$

That is, the joint resistance is equal to half the resistance of one conductor.

152. Three or More Conductors in Parallel.—The same general principles apply when three or more conductors are connected in parallel. For three conductors whose separate resistances are R_1, R_2, and R_3, Fig. 93a, the joint resistance may be calculated by the following relation:

$$I = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

$$= E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

But $I = \frac{E}{R}$, where R is the joint resistance, and

$$\text{hence, } \frac{E}{R} = E\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R} = \frac{R_2R_3 + R_1R_3 + R_1R_2}{R_1R_2R_3}$$

Whence by taking reciprocals, we again get,

$$R = \frac{R_1R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3}$$

which means that the joint resistance of three conductors is equal to the product of the resistances divided by the sum of the products obtained by multiplying together two of the resistances at a time.

EXAMPLE

Find the joint resistance of 3 conductors whose separate resistances are 2, 3, and 4 ohms respectively.

Solution.—

$$R = \frac{R_1 \times R_2 \times R_3}{R_1R_2 + R_1R_3 + R_2R_3}$$

$R_1 = 2$ ohms, $R_2 = 3$ ohms, $R_3 = 4$ ohms

$$\text{Then } R = \frac{2 \times 3 \times 4}{2 \times 3 + 2 \times 4 + 3 \times 4}$$

$$= \frac{24}{6 + 8 + 12} = \frac{24}{26} = \frac{12}{13} \text{ ohms}$$

In general, we can calculate the joint resistance of any number of conductors connected in parallel in exactly the same way. It is not necessary to show how any more formulas are calculated. A general rule will suffice. *To find the joint resistance*

of any number of parallel resistances, divide the product of all of the resistances by the sum of the products obtained by multiplying together all of the resistances less one. The same resistance must not appear in any one product more than once.

EXAMPLE

Find the joint resistance of five resistances R_1, R_2, R_3, R_4, and R_5.

Solution.—The product of the resistances is $R_1 \times R_2 \times R_3 \times R_4 \times R_5$. Since there are 5 resistances, the divisor must contain the products obtained by taking four resistances at a time. The only possible products we can make, using each resistance only once in each product, are

$$\begin{aligned}
&R_1 \times R_2 \times R_3 \times R_4\\
&R_1 \times R_2 \times R_3 \times R_5\\
&R_1 \times R_3 \times R_4 \times R_5\\
&R_2 \times R_3 \times R_4 \times R_5\\
&R_1 \times R_2 \times R_4 \times R_5
\end{aligned}$$

and $$R = \frac{\text{product of five resistances}}{\text{sum of products taken 4 at a time}}$$

Suppose $R_1 = 2$, $R_2 = 3$, $R_3 = 4$, $R_4 = 5$, and $R_5 = 10$

Then
$$\begin{aligned}
R_1 \times R_2 \times R_3 \times R_4 \times R_5 &= 2 \times 3 \times 4 \times 5 \times 10 = 1200\\
R_1 \times R_2 \times R_3 \times R_4 &= 120\\
R_1 \times R_3 \times R_4 \times R_5 &= 400\\
R_1 \times R_2 \times R_4 \times R_5 &= 300\\
R_1 \times R_2 \times R_3 \times R_5 &= 240\\
R_2 \times R_3 \times R_4 \times R_5 &= 600\\
\text{Sum} \quad & \overline{1660}
\end{aligned}$$

and $R = \dfrac{1200}{1660} = \dfrac{60}{83}$ ohms

153. Practical Applications.—Parallel conductors are used extensively in practice. All cables and flexible conductors are

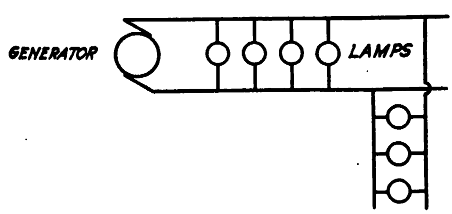

FIG. 94.

in reality a bundle of parallel wires. In alternating current power transmission, it is often preferable to use stranded conductors in preference to solid conductors. Incandescent lamps are almost always connected in parallel as indicated in Fig. 94.

Fig. 95.

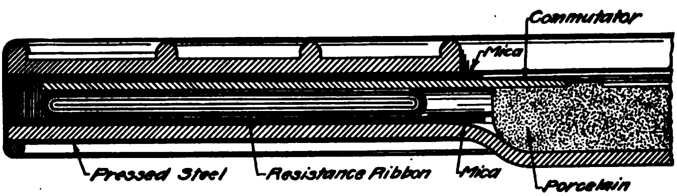

Fig. 96.

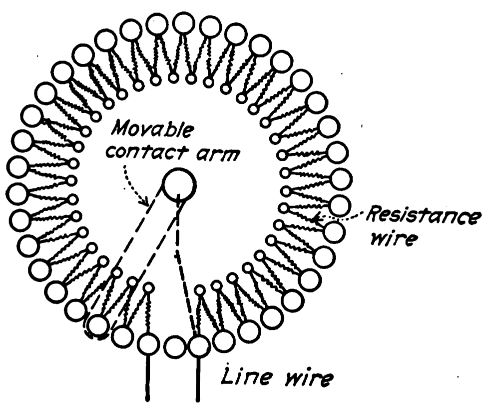

Fig. 97.

The resistance of the lamps thus decreases with the increase in the number of lamps.

FIG. 98.

Nearly all current-controlling apparatus consists of merely a combination of wires or metal in some form whose resistance is effective in regulating the current. Thus motor starters and field

FIG. 99.

resistances are rheostats whose resistance may be varied. One type of field rheostat is shown in Fig. 95. These field rheostats consist of a circular base plate of insulating material to which is

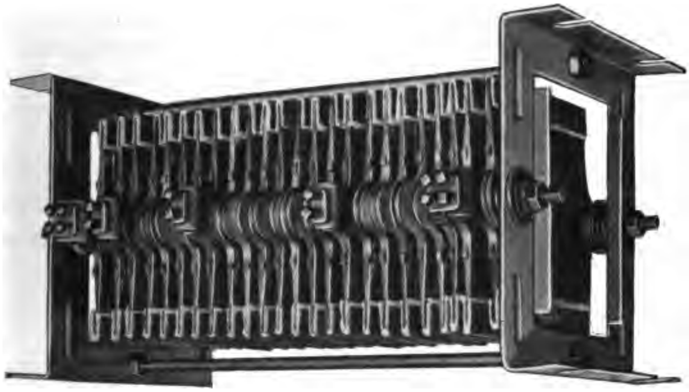

FIG. 100.

attached the resistance wire, contacts and lever, the whole being enclosed in a ventilated, japanned iron case of attractive design. A cross-section of the rheostat showing the construction is shown in Fig. 96. The manner in which the resistance of this type of field rheostat is increased or decreased will be understood from Fig. 97.

For motor starting the rheostats are also made in many different forms. One form for mounting on the wall or a panel board is shown in Fig. 98. The type of resistance used is shown in Fig. 99. For the control of series street railway motors the resistances are usually made in the form of grids shown in Fig. 100.

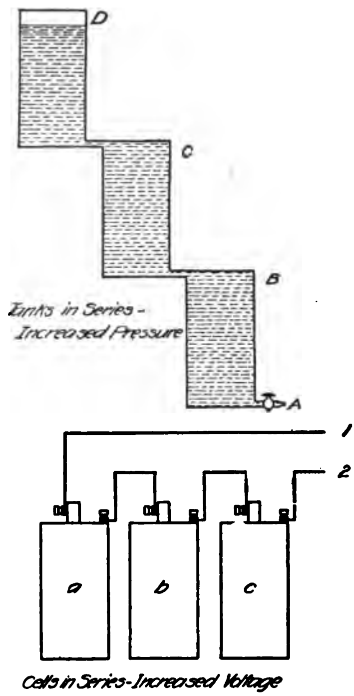

FIG. 101.

154. Cells in Series.—Although in most of the experiments discussed so far two or more cells in series have been employed, the principles that govern such a connection have not been explained. In the discussion of Ohm's law it was stated that E,

the pressure, must be the total electromotive force in the circuit. What is the total electromotive force when cells are connected in series as shown in Fig. 101? The analogous diagram of tanks in series may help to make this clear. The hydrostatic pressure at A is evidently the sum of the pressures due to the elevations of the water $AB+BC+CD$. That is, it is the sum of the pressures of the separate tanks. Similarly, the electrical pressure between the terminals 1 and 2 is the sum of the pressures across cells a, b, and c.

155. Experiment 35. To Study the Pressure of Cells in Series.

Apparatus.—

Volt-ammeter.

Three dry cells.

Operation.—The manner of connecting the volt-ammeter to the cells has been explained in detail so many times that hereafter detailed explanations will be omitted.

Take three dry cells and measure the voltage of each separately. Record these thus:

VOLTAGE OF CELLS

	Cell (a)	Cell (b)	Cell (c)	Total
1	1.40	1.45	1.35	4.20
2				
3				
4				
Mean				

Then connect two cells in series and measure the voltage across both. Compare the voltmeter registration with the sum of the voltages of the two cells. Next connect the three cells in series exactly as indicated in Fig. 101 and measure the voltage across all three cells. Compare this value with the sum of the three voltages. Does the experiment show that the total voltage of cells in series is equal to the sum of the several voltages?

Reverse the connection of one of the cells and again measure the total voltage. Is it the same as before? Why?

156. Theory.—When cells are connected so that the pressure of each is in the same direction, the total pressure is equal to the sum of the several pressures. In general, if E is the pressure of one cell and n cells are connected in series, the total pressure is nE.

EXAMPLE

What is the total pressure when 5 Daniell or gravity cells are connected in series?

Solution.—The pressure of one gravity cell is approximately 1.1 volts; hence of five cells in series the pressure is $5 \times 1.1 = 5.5$ volts.

157. Battery Resistance for Series Connections.—It must be noted that as each cell connected has some internal resistance, connecting cells in series is the same as connecting wires in series. That is, the resistance of the battery is the sum of the resistances of the separate cells. If r represents the internal resistance of one cell, the resistance of a battery of n cells is nr.

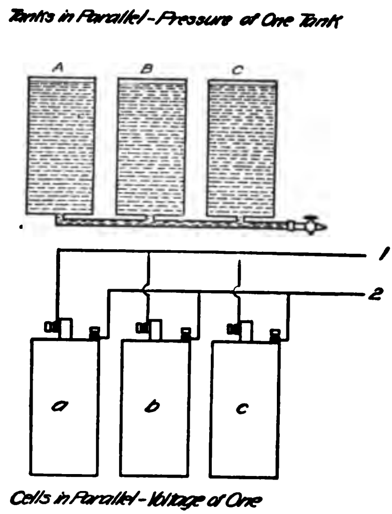

Fig. 102.

158. Cells in Parallel.—Fig. 102 is a diagram of tanks and cells connected in parallel. It is evident that the hydrostatic pressure exerted by the water in tank A is the same as that in B and C, since the height of the water is the same in each. The total pressure is equal to that of one tank. The three tanks could be replaced by one large tank, and as long as the water was maintained at the same height, the pressure at the orifice would be exactly the same in the two cases.

When cells are connected in parallel the total pressure is equal to the pressure of one cell, and the three cells a, b, and c can be replaced by one large cell having the same cross-section of zinc and carbon as the three cells taken together.

When tanks are connected in parallel it is evident that each supplies only a part of the current. The same principle holds with reference to cells connected in parallel—each cell supplies only a part of the total current. The student can readily verify the law of pressures by connecting three cells in parallel and then connecting the voltmeter to terminals 1 and 2, Fig. 102, and comparing the voltmeter reading with the reading given when the voltmeter is connected to each cell separately.

159. Battery Resistance for Parallel Connections.—The effect of connecting cells in parallel is to increase the current capacity and decrease the internal resistance. In so far as the internal resistance of one cell is concerned, it may be considered as a conductor whose resistance is r. Three cells in parallel will thus be the equivalent of three resistances in parallel. It has been shown that when three equal resistances are in parallel, the joint resistance is equal to one-third of the resistance of one wire. Accordingly, the joint internal resistance of a battery of m parallel cells is $\frac{r}{m}$.

EXAMPLE

Five cells each having an internal resistance of 1 ohm are connected in parallel. What is the joint resistance?

Solution.—Since the resistances of the cells are the same, the joint resistance is 1/5 of 1 ohm = 0.2 ohm.

160. Series Parallel Connection.—In some instances it is advisable to connect several series groups in parallel; such a

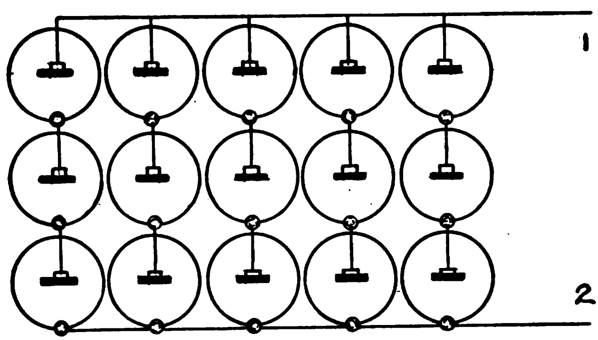

Fig. 103.

connection is shown in Fig. 103. The total pressure between terminals 1 and 2 is equal to the pressure of one series group. The internal resistance of such an arrangement is equal to the resistance of the cells in series divided by the number of groups connected in parallel. Using the same notation as before, if r represents the resistance of one cell, the internal resistance of n cells in series is nr ohms. If, now, m series groups are connected in parallel, the joint resistance is $\frac{nr}{m}$ ohms.

EXAMPLE

If the internal resistance of each cell is 2 ohms, what is the battery resistance of Fig. 103?

***Solution.*—There are three cells in series and five series groups in parallel; hence the joint resistance is**

$$R=\frac{nr}{m}=\frac{3\times 2}{5}=1\tfrac{1}{5}\text{ ohms}$$

161. Ohm's Law as Applied to Cells in Series and Parallel.—It has been mentioned several times that in determining the current by Ohm's law it is necessary to take into consideration the internal or battery resistance. When cells are connected in series only, this internal resistance is nr, and the pressure is

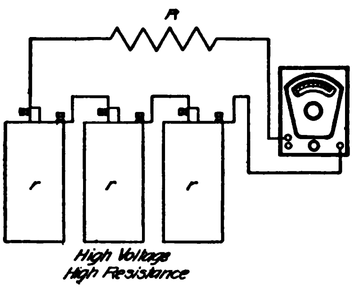

Fig. 104.

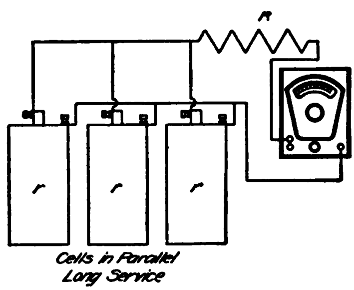

Fig. 105.

nE, where E is the pressure of one cell. If R represents the external resistance then by Ohm's law the current is

$$I=\frac{nE}{R+nr}$$

Such a connection is shown in Fig. 104.

The current given by a parallel connection can be calculated in the same way. The total pressure is equal to that of one cell, and as the internal resistance is $\frac{r}{m}$, the current in a circuit whose external resistance is R is

$$I=\frac{E}{R+\frac{r}{m}}.$$

A diagram of such a connection is shown in Fig. 105.

If cells are connected in series-parallel as shown in Fig. 103, the current through an external resistance R is then $\frac{nE}{R+\frac{nr}{m}}$

EXAMPLE

What current will flow through a 2-ohm coil connected to terminals 1 and 2, Fig. 103, if each cell has a pressure of 1.4 volts and an internal resistance of 1 ohm?

Solution.—

$$E = 1.4$$
$$n = 3$$
$$r = 1$$
$$m = 5$$
$$R = 2$$

Then $$I = \frac{nE}{R + \frac{nr}{m}} = \frac{3 \times 1.4}{2 + \frac{3 \times 1}{5}}$$
$$= \frac{4.2}{2\frac{3}{5}} = \frac{4.2}{2.6} = 1.6 \text{ amperes, nearly.}$$

162. Best Grouping of Cells.—Whether a certain grouping of cells is better than another will depend upon the conditions of service. If cells are to be used in such a way as to have a long life, that is, if they are to have a long life and comparatively high efficiency, the parallel grouping is preferable. When such a grouping is used, the materials of the cells will be consumed slowly, and there will be a minimum waste of energy.

If it is desired to obtain the greatest possible current from a given number of cells, and the cells are to be grouped in series-parallel only, the best manner of grouping them will be such as to make the internal resistance of the battery equal to the external resistance. Although this arrangement gives the strongest current, it is not the most efficient; for, if the internal and external resistances be equal to one another, the useful work in the external part of the circuit is only half the total energy. The other half of the energy is wasted inside of the cells.

EXAMPLE

Given six cells each having 2 volts pressure and 2 ohms internal resistance, how should the cells be connected to give the greatest current through a 3-ohm coil?

Solution.—In order that the current may be a maximum, the internal resistance must equal the external resistance.

Let n = number cells connected in series
m = parallel groups
then $n \times m = 6$

The internal resistance is $\frac{n \times 2}{m}$, but this must equal 3 ohms.

$$\text{Then } \frac{n\times 2}{m}=3$$

$$2n=3m$$

$$\text{But}\quad m=\frac{6}{n}$$

$$\text{then}\quad 2n=\frac{3\times 6}{n}$$

$$2n^2=18$$

$$n^2=9$$

$$n=\sqrt{9}=3=\text{number of cells in series}$$

$$m=\frac{6}{3}=2 \text{ parallel groups}$$

When such a connection is made, the current is

$$I=\frac{3\times 2}{3+\frac{3\times 2}{2}}=\frac{6}{6}=1 \text{ ampere}$$

No other grouping of the cells will give any greater current. For instance, if the cells had been connected two cells in series and in 3 parallel groups, the current would have been

$$I=\frac{2\times 2}{3+\frac{2\times 2}{3}}=\frac{4}{4\frac{1}{3}}=\frac{12}{13} \text{ ampere}$$

In the discussion of electromagnets it was shown that self induction prevented the sudden rise of current in such a circuit. The time during which the circuit is closed also helps determine the maximum current that will flow through such a circuit. The time required for the current in an inductive circuit, such as an electromagnet or induction coil, to reach a certain per cent of its maximum value as indicated by Ohm's law, is determined by the ratio of the inductance and resistance. This ratio, $\frac{L}{R}$, is known as the *time constant* and the smaller this ratio the more quickly does the current reach a relatively large value. This ratio is small when R is large, and R is large relatively when cells are connected in series. Hence when cells are used on inductive circuits, quick action is secured by connecting the cells in series.

RECAPITULATION

1. According to *Ohm's Law* the current in a circuit is directly proportional to the pressure. For direct-current circuits it is usually expressed thus,

$$I=\frac{E}{R}$$

Where I is current in amperes, E is the pressure in volts and R is the resistance in ohms.

2. By *capacity* is meant the property of a conductor or a system of conductors for storing electricity. The unit of capacity is the *farad.* A *farad* is that capacity which will be charged to a difference of one volt by coulomb; a *micro-farad* is one-millionth of a farad.

3. When resistances are connected in series, the joint resistance is equal to the sum of the resistances connected.

4. By *voltage drop* is meant the fall of electrical pressure between two points on a conductor. It is equal to the product of the current by the resistance between the two points. Algebraically it may be written

$$e = IR$$

5. The *joint conductivity* of several resistances connected in parallel is equal to the sum of the separate conductivities, and the joint resistance of several resistances connected in parallel is the reciprocal of their joint conductivities. To find the joint resistance of any number of parallel conductors divide the product of all of the resistances by the sum of the products obtained by multiplying together all of the resistances less one. The same resistance must not appear in any one product more than once.

6. When cells are connected in series the total pressure is equal to the sum of the pressures of the cells. The internal resistance is equal to the sum of the resistances of the several cells.

7. When cells are connected in parallel, the resulting pressure is the pressure of one cell. The internal resistance is equal to the resistance of one cell divided by the number of cells.

8. Cells may be grouped in series-parallel. When so connected the total pressure is equal to the number of cells in series. When a series-parallel group of cells is connected to resistance R, the current is given by

$$I = \frac{nE}{R + \frac{nr}{m}}$$

Where E is the pressure of one cell, n is the number of cells in series, m is the number of series groups connected in parallel and r is the internal resistance of one cell.

9. When cells are to be grouped for maximum current output, and only the series-parallel grouping is to be employed, they are to be grouped so that the internal resistance equals the external resistance.

CHAPTER IX

INDUCED CURRENTS AND PRINCIPLES OF THE ELECTRIC GENERATOR AND MOTOR

163. Introduction.—Some of the most elementary principles of inducing an electromotive force were discussed briefly in Chapter III. It was there shown that whenever a permanent magnet was inserted or removed quickly from a solenoid the ends of which were connected to a galvanoscope, the compass needle was deflected. The amount of the deflection was determined by the rapidity with which the magnet was moved, and the direction of deflection depended upon whether the *N*- or *S*-pole was being inserted or withdrawn. It was also shown that the direction of the induced current was in every case such that the magnetic field due to the current opposed the motion of the bar magnet. We shall now investigate these principles more fully, and learn how they are applied in practice.

164. The Generator.—A simple generator or motor is among the apparatus sent the student. A drawing of this is shown in Fig. 106. Comparing this drawing with the apparatus the student will observe that *C* is an iron core around which have been wound two coils of insulated wire. The two free ends of the coils are connected to two halves of a split brass cylinder on the shaft by means of two screws. The two pieces of brass cylinder are insulated from each other and from the iron shaft by a fiber cylinder to which the brass pieces are fastened. The iron core, *C*, Fig. 106, with its windings is called the armature, and the split brass cylinder is called the commutator. Both armature and commutator are mounted on a shaft which permits of their rotation.

Resting on opposite sides of the commutator are two copper wires called brushes. These brushes are attached to two holders which in turn are held in place by two binding posts *A* and *B*. The electric circuit then begins at one binding post, continues through one brush holder and brush to one commutator segment, then through the winding on the armature to the other commu-

tator segment, through the other brush and brush-holder, and back to the other binding post.

Within two wooden blocks are two bar magnets M–M'. These are movable around two screws at the ends of the blocks as centers. By means of such a mounting the two bar magnets can be moved with reference to the armature.

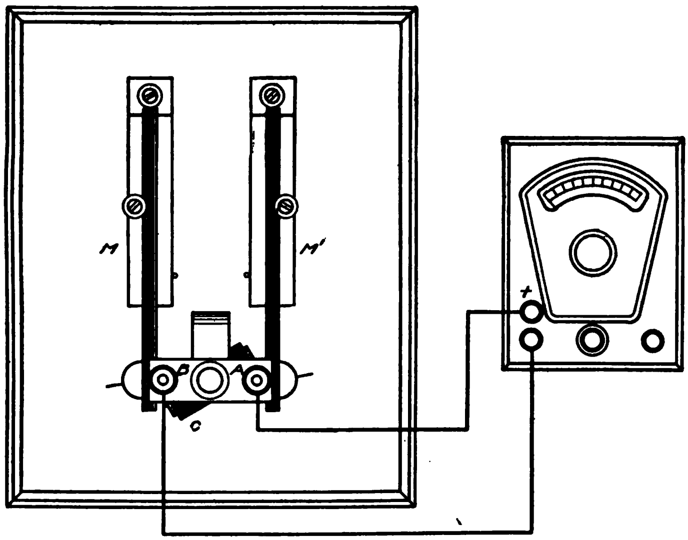

FIG. 106.

165. Experiment 36. To Study Principles of the Electric Generator.

Apparatus.—

Generator on board
Volt-ammeter

Operation.—Connect the volt-ammeter to the binding posts of the generator as shown in Fig. 106. Wrap a string around the shaft above the commutator in the same manner as a string is wrapped around the stem of a top or gyroscope. If a grooved pulley is available, a better plan is to make a string belt and pass it around the grooved pulley and shaft of the armature above the commutator. By turning the grooved pulley the armature may be caused to rotate at a high speed and the speed can also be varied at will. The driving wheel of a sewing machine may be utilized for this purpose.

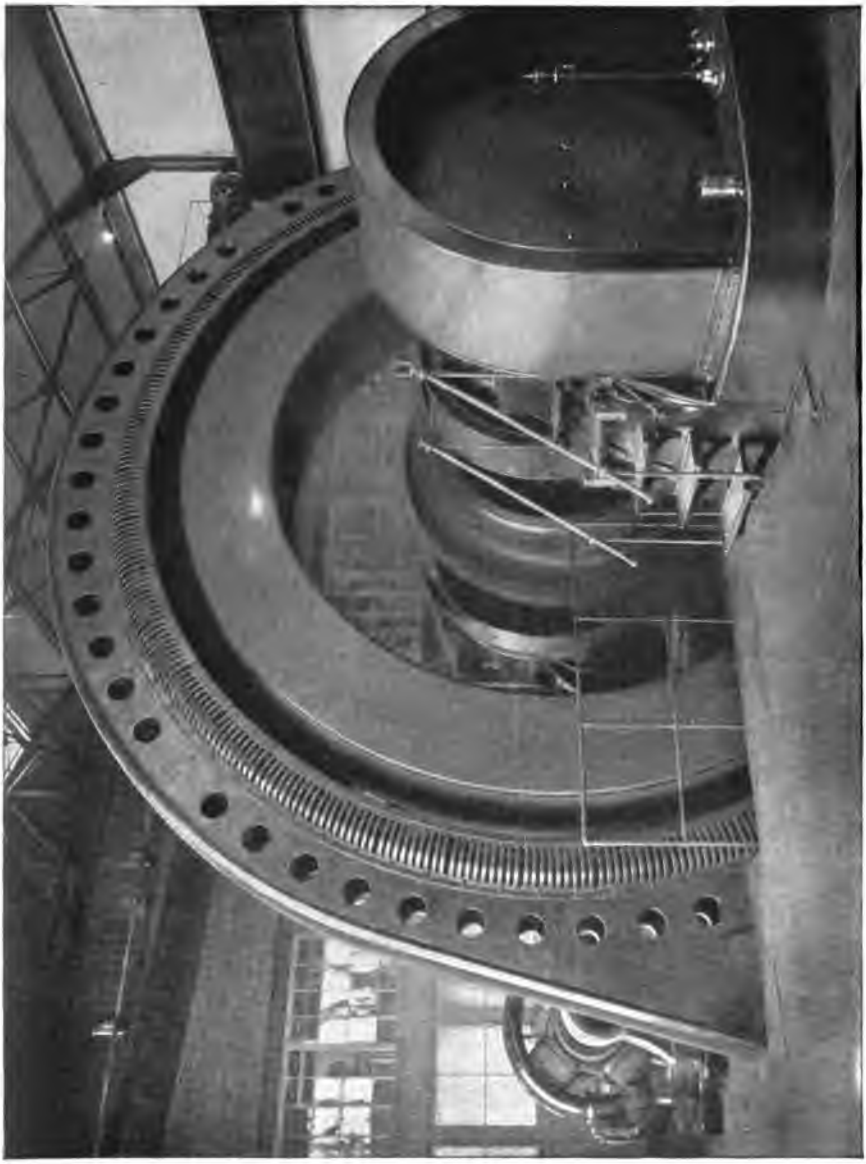

PLATE 5.—One 1500-kilowatt Allis-Chalmers fly-wheel type alternating current generators.

See that opposite poles of the bar magnets are near the armature; press down the button on the ammeter and cause the armature to rotate rapidly by pulling on the string, or by turning the driving wheel. While the armature is in motion observe the pointer of the ammeter. Does it deflect? In which direction? Reverse the direction of rotation of the armature and again observe the ammeter pointer. Does the direction of the deflection of the pointer depend upon the direction of rotation of the armature? Turn the bar magnets end for end and repeat. Does the direction of the deflection depend upon the polarity of the bar magnets? If possible maintain the speed of rotation constant and observe whether the pointer remains nearly stationary.

Can you explain why the deflection of the pointer is always in one direction as long as the armature rotates in one direction? If the student will refer to his results of experiment 18 he will see that the compass needle was deflected in one direction when the magnet was withdrawn. What accounts for the different behavior of the compass needle and pointer of the ammeter?

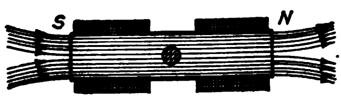

FIG. 107a.

166. Theory.—In experiment 18 the coil was held stationary while in this experiment the magnets are stationary and coils are rotated. When the opposite poles of the two bar magnets are near the armature, the magnetic field extends from one to the other as was demonstrated by the student in experiment 5. A diagram of this field is shown in Fig. 107a. The magnetic lines pass from the N-pole of one bar magnet through the armature core to the S-pole of the other magnet. As the armature rotates the winding cuts across these lines as indicated in Fig. 107b. The magnetic lines enter the coil from the side A at first, but when the armature has made one-half of a rotation, the lines enter from the side B. During this half rotation the direction of the lines within the core has reversed, and according to the principles of experiment 18 an electromotive force must be induced in the windings while this relative motion takes place. Furthermore, it must be clear that if the direction of the magnetic lines with reference to the armature coils is reversed every half rotation the induced electromotive force must be in one direction during one half of the rotation, and in the opposite

direction during the other half of the rotation; and yet the student saw that the pointer of the ammeter was deflected in only one direction. The question is, how was this accomplished? The student perhaps already surmises that the commutator has something to do with this.

An examination of the apparatus will show that the brushes rest on diametrically opposite points of the commutator, and that at no time, or for only the briefest instant during the rotation of the commutator, do the brushes rest on the same segment

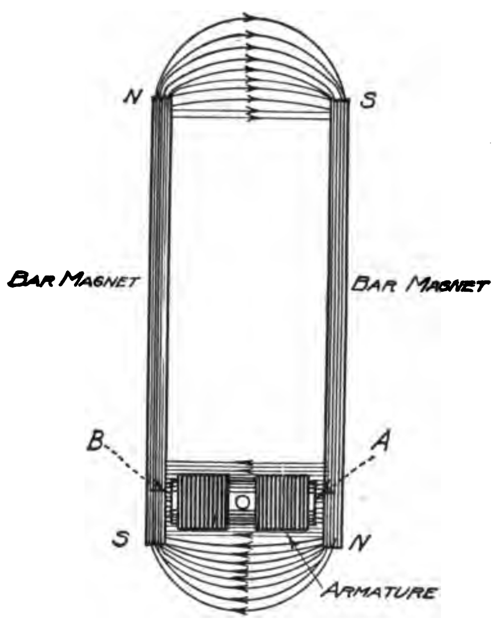

FIG. 107b.

of the commutator. As the armature rotates the brushes make contact first with one segment, and after a half rotation, with the other segment. Thus if the current in the armature coil is in such a direction as to come out at the binding post B, Fig. 106, during the first half rotation, it must also flow out at the same binding post during the second half of the rotation; for where the direction of current in the armature coils is reversed, the commutator segments have changed brush contacts. The commutator thus serves to reverse or exchange the connections

of the armature coil at every half rotation. While the current in the armature coils reverses its direction of flow every half rotation, that in the external circuit flows continuously in one direction. The purpose of the commutator is thus to convert the alternating armature current into a uni-direction, or one direction, current in the external circuit. A direct-current generator armature with commutator is shown in Fig. 108.

The electromotive force is induced in the windings of the armature in exactly the same way as in experiment 19. The magnetic field is due to the two bar magnets when placed so that opposite poles are near each other. That unlike poles must be adjacent in order that an electromotive force may be induced can be shown easily by turning one of the magnets end

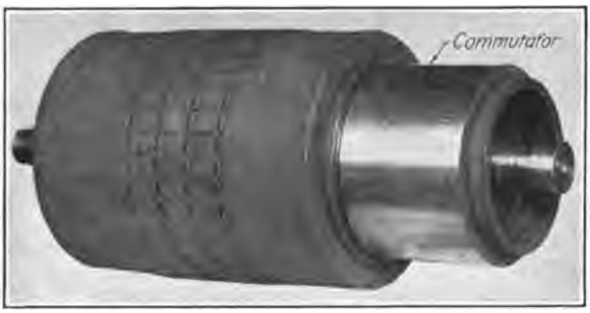

FIG. 108.

for end and repeating the experiment. When this is done it will be seen that no electromotive force is generated.

167. Experiment 37. To Study the Relation of Induced Electromotive Force to Speed.

Apparatus.—Same as for experiment 36.

Operation.—Connect the apparatus as before and rotate the armature first slowly and note the deflection of the pointer of the ammeter. Next rotate it at a higher speed and again note the deflection. Has it increased or decreased? Repeat once more by turning the armature at still a higher speed and again observe the deflection. Can you make any deduction as to the increase or decrease of the electromotive force with speed?

168. Theory.—From the results obtained no exact mathematical relation between the strength of the induced electromotive force and speed can be given, for neither the speed nor the

pressure was measured, but even so simple an experiment shows that the higher the speed the higher the electromotive force induced. The strength of the magnetic field is kept constant, the number of turns on the armature is the same; hence as the speed is the only factor that is changed we are justified in saying that the induced pressure depends upon the speed of the armature, increasing as the speed increases and decreasing as the speed decreases.

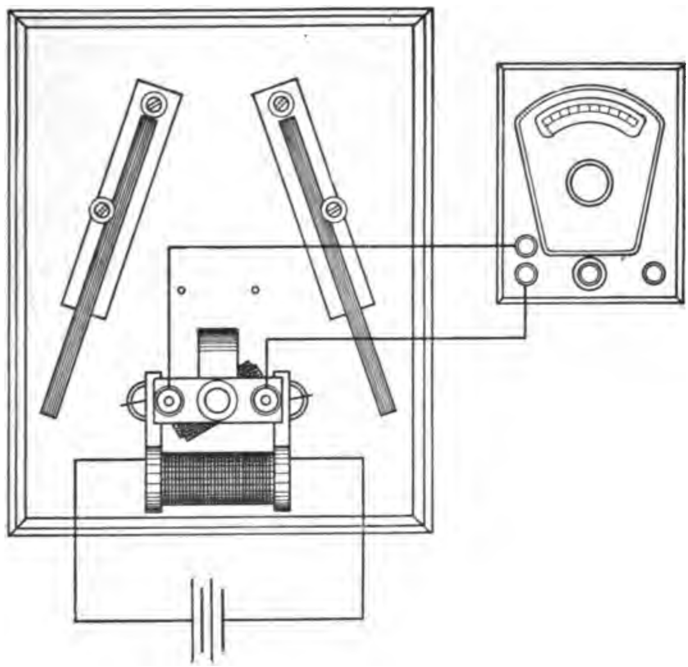

FIG. 109.

169. Experiment 38. To Study the Relation between Strength of Magnetic Field and Induced Electromotive Force.

Apparatus.—

Volt-ammeter
Generator
Two dry cells
Electromagnet

Operation.—First connect the apparatus as in experiment 37. Place the opposite poles of the bar magnets near the armature

and rotate the armature at quite a high speed. Observe the deflection. Move the bar magnets about half an inch away from the pegs in the center of the board and again rotate the armature at the same speed. How does the deflection of the ammeter pointer compare with that previously made? Move the bar magnets another half inch and repeat. Repeat this until no deflection is observed.

Next swing the bar magnets entirely to one side and place the electromagnet in position as shown in Fig. 109. Connect one dry cell to the electromagnet terminals and rotate the armature as before. What deflection do you now observe? Repeat the experiment by connecting two cells in series with the electromagnet. Does the deflection vary with the strength of the magnetic field? If so, how?

170. Theory.—This experiment illustrates another fundamental principle of the generator. The results show that as the bar magnets are moved out the induced voltage decreases. This is due to the decrease in the strength of the magnetic field. When the electromagnet was used in place of the permanent magnets the deflection was greater. This was due to the fact that the electromagnet provides a stronger magnetic field.

As the armature is so constructed that the number of turns cannot be changed readily the relation between the number of turns on the armature and the induced voltage cannot be shown by means of a simple experiment. This relation has, however, been explained in Chapter III where it was shown that the induced pressure is proportional to the number of turns in series on the armature. These principles have been expressed in algebraic form as follows:

$$E=\frac{n\ \Phi}{t\times 10^8}$$

where n is the number of turns, Φ is the total magnetic flux, t is the time, in seconds, of cutting, and 10^8 $(=100{,}000{,}000)$ is a factor necessary for converting the value of induced pressure into volts.

171. Kinds of Generators.—Electric generators are classified in accordance with the manner of excitation; that is, the classification is determined by the manner in which the magnetic field is produced. There are thus magneto, series, shunt, compound and separately excited generators.

The magneto generator was illustrated when the field was pro-

duced by the permanent magnets. Such generators are never built in very large sizes, although they are extensively used for ringing telephone bells, and for supplying current for gas and gasoline engine ignition.

172. Series Generator.—The principles of the series generator were not illustrated. In a series wound generator the electromotive force of the generator supplies the current for excitation. The current developed in the armature flows through the windings of the field as shown in Fig. 110.

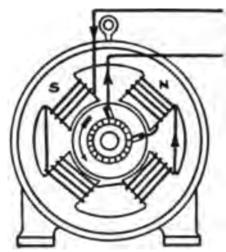

Fig. 110.

173. Shunt Generator.—In a shunt generator, the field is excited by a winding that is connected in parallel with the outside circuit. The exciting current can circulate through the field winding no matter whether the external circuit is closed or open. A diagrammatic sketch of such a generator is shown in Fig. 111. The student will observe that one end of the field winding is connected to one brush at *a* and after passing around the field poles and the regulating rheostat it is connected to brush *b*. The current developed in the armature divides at the brushes; part of it passes through the field winding while the other part passes through the external circuit. By means of the rheostat the current through the field winding is regulated.

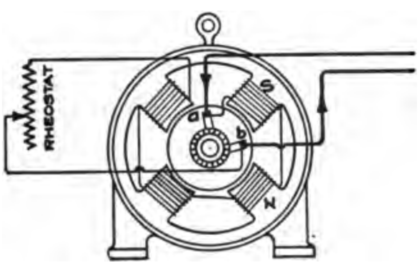

Fig. 111.

174. Compound Generator.—Both the series and shunt generators have certain disadvantages which are eliminated by a combination of the two windings. Such a machine is called a compound generator. The manner in which the winding is arranged is shown in Fig. 112.

The principles of separate excitation were illustrated by the experiment in which the electromagnet was used. In this experiment the excitation was supplied by the dry cells. In practice dry cells are not used, but usually a small shunt or compound generator is employed. This is the method used in nearly every alternating-current generator.

PLATE 6.—Testing floor, Westinghouse Electric and Mfg. Co.

175. The Electric Motor.—A direct-current generator may be used as a motor with but slight modification. The difference between a direct-current generator and a direct-current motor is not in their mechanical construction, but in their manner of operation. A generator is driven by mechanical means, and in its operation converts mechanical energy into electrical energy. The motor is driven by electrical means and converts electrical energy into mechanical energy. We have learned some of the principles of generating an electromotive force and some of the characteristics of a dynamo when operated as a generator. We will now study how an electric current can cause a dynamo to operate as a motor, and some of the characteristics of the machine when so operated. In order to get a clear understanding of the fundamental principles several experiments will have to be performed.

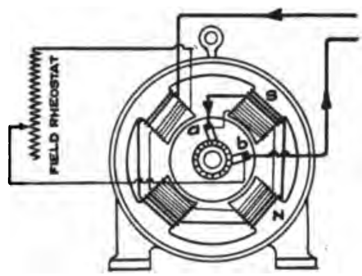

FIG. 112.

176. Experiment 39. To Investigate the Cause of Rotation of Motor Armature.

Apparatus.—

Motor on board

Two dry cells

Operation.—First carefully examine the winding on the armature and note carefully the direction taken by a current if the positive terminal of a dry cell is connected to binding post *A*, Fig. 113. Place the armature in the position indicated in the figure, and determine the polarity of the ends of the armature, assuming that the current flows in at *A* and out at *B*. If you cannot do this by means of the right-hand rule, swing the bar magnets apart and remove one magnet from its holder. Connect the carbon electrode of one dry cell to binding post *A* and the other or cup to binding post *B*. With the armature in such a position that each brush touches only one commutator segment determine the polarity of the armature by testing with the bar magnet. This can be done without touching the magnet to the armature core. If the pole of the armature is opposite to that of the end of the bar magnet a strong attraction will result. Is the polarity as expected? Replace the bar magnet within

its holder and after disconnecting the battery swing the magnets into place. Assuming that the current enters at the binding post A, and remembering that unlike poles attract, will the end of the armature marked C be attracted by the N-pole or by the S-pole of the bar magnet? That is, in which direction will the armature turn, clockwise or counter-clockwise? Now connect the cell as before and verify your conclusions. Hold the armature so that it comes to rest with its long axis parallel to the magnetic field. Note the position of the brushes. Turn the armature by hand in the direction of rotation until the brush contacts change segments. What happens? Why does the armature move? Has the polarity of the armature changed? How can you account for this? Why does it not stop after making a complete one-half revolution?

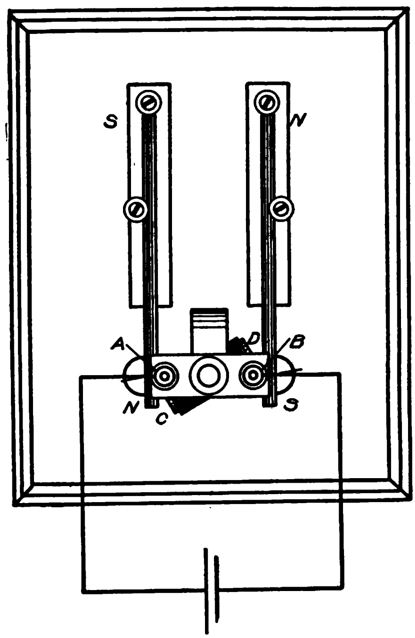

Fig. 113.

177. Theory.—A careful performance of the foregoing experiment and a thorough study of the principles will give the student a clear understanding of the cause of rotation of the armatures of all motors. In many cases these principles are combined with others and thus the whole process is much more complicated but the elements are the same in every case. The cause of rotation can be briefly stated to be due to the interaction of two magnetic fields. One field is due to the permanent magnets which remain fixed in position. The other is due to the current flowing through the armature winding. This field reverses its direction every time the commutator segments change brush contacts.

In the first part of the experiment the student learned that the end C of the armature core is a S-pole while D is a N-pole. The

ends of the bar magnets are of opposite polarity with respect to the polarity of the armature core. These two poles are attracted to each other, causing the armature to move counter-clockwise. When the armature has moved a little beyond the middle point, the brushes change connection with the commutator segments thus changing the direction of the current through the armature and as a consequence the polarity of the armature core is also changed. The end that was a N-pole becomes a S-pole, and vice versa. Thus the end C of the armature core instead of being attracted by the adjacent pole of the bar magnet is repelled. The same conditions prevail at the end D of the armature. When the armature has made one-half of a rotation the brushes again change commutator segments and thus the armature continues to rotate.

178. Experiment 40. To Determine the Direction of Rotation.

Apparatus.—Same as in preceding experiment.

Operation.—Exchange the battery connections and with the magnets in position observe the direction of rotation of the armature. Has it reversed? Can you explain why? Loosen the nuts that hold the bar magnets in place and change them end for end, and again determine the direction of rotation. What conditions determine the direction of rotation? Turn the brush holder around as far as it will go and see if the armature will rotate. Why?

One method of varying the speed is by shifting the brushes. With two cells connected in series and the motor running freely, turn the brush holder slowly first in one direction and then in the other and observe the effect on the speed. Explain this.

179. Experiment 41. To Study the Relation between the Strength of the Magnetic Field and the Speed of Rotation.

Apparatus.—Same as in Experiment 39.

Operation.—Connect one cell, ammeter, and motor in series and while the armature is in rotation spread the bar magnets and observe whether the speed decreases or increases. Does the strength of the magnetic field affect the speed? How? Read the armature current. Replace the magnets and connect two cells, the ammeter, and motor in series and compare the resulting speed with the speed when only one cell was connected to the motor. Also read the resulting current. Does the speed vary with the current through the armature? How?

180. Theory.—The student will have to be careful in making general conclusions from the results of experiments 40 and 41. While the results of experiment 41 show that the speed decreases as the bar magnets are moved out it would seem that a decrease in the field strength decreases the speed. This, however, is true only under certain conditions. It would lead to great error to assume that such is the case in practice. The reason for this seemingly false conclusion will be stated now, and the principles will be illustrated by an experiment later. In the present experiment the friction of the brushes, bearings, and air is so great in comparison with the torque, that when the bar magnets are moved out the field is weakened and consequently the torque and speed is decreased. By torque is here meant the turning effort or moment which is produced by the interaction of the magnetic fields due to the current in the armature windings and bar magnets. This torque is proportional to the product of these two fields.

The field due to the armature current is proportional to the current and in this experiment this current is almost entirely determined by the resistance of the circuit which consists of the cell, connecting wires, brushes, commutator, and armature windings. If this were not so, a different result would be observed. In the second part of the experiment, another cell was added and accordingly the armature current was increased. This increase in armature current strengthens the armature field and the resulting torque. As the torque is increased the speed is increased.

It has already been pointed out that if we were restricted to the use of permanent magnets, dynamos of large capacity would be unknown. The next experiment, then, will be to determine the effect of using an electromagnet for the field and to study some characteristics of practical motors.

181. Experiment 42. To Study the Characteristics of a Separately Excited Motor.

Apparatus.—

Motor and electromagnet
Dry cells
Volt-ammeter

Operation.—Connect the volt-ammeter, one dry cell, and electromagnet in series as indicated in Fig. 114 and then connect one cell to the armature binding posts. By holding your finger against the armature shaft test the torque. Is the torque greater

or less than when permanent magnets were used? Why? With one of the bar magnets test the polarity of the electromagnet. Is the electromagnet any stronger than the bar magnets? If so, do you think this has anything to do with the torque?

Next, connect two dry cells in series with the field and again observe the speed. Has the speed increased or decreased? Can you account for the change? In each case read and record the field current. After measuring the current through the field, remove the volt-ammeter and connect it into the armature

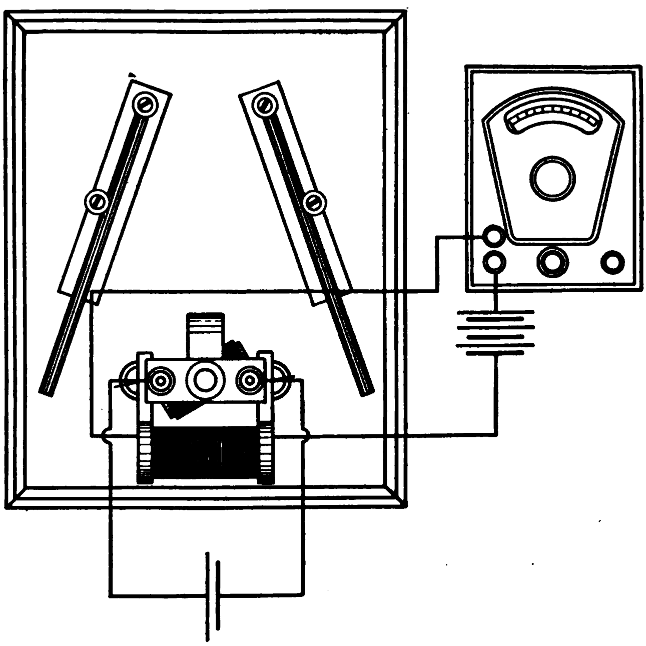

FIG. 114.

circuit; close the armature circuit and read the current when the armature is stationary. Then close the field circuit and start the armature. Observe the behavior of the ammeter pointer while the motor is speeding up. Does the current increase or decrease? Explain. Repeat this until you are certain that you have made no mistake in reading the ammeter.

182. Theory.—The general principles of the operation of the motor are the same in this as in the preceding experiments. The only difference is in the field strength. That is, the electro-

magnet field is much stronger than the permanent magnet field. The magnetic field, however, is not as strong as it ought to be on account of the large air gap. Commercial motors are constructed so that the magnetic field has only a small air gap to cross, and this air gap remains fixed in depth. The iron cores for the magnetic field of Type S, Northern motor, is shown in Fig. 115, and a diagram showing the path of magnetic lines is shown in Fig. 116. The most puzzling result is undoubtedly the last part of the experiment where it is shown that the armature current decreases as the speed increases. This is due to two causes. One

Fig. 115.

is the increase in the resistance of the brush contacts, for as the speed increases the brushes are jarred as they pass over the slots. This jarring increases the resistance and decreases the current. The decrease in current is not wholly due to the increase in resistance, as a little reasoning will show.

In experimenting with the dynamo as a generator it was shown that as the armature rotated within the magnetic field, an electromotive force was developed which caused a deflection of the ammeter. The same conditions for generating an electromotive force are present in this experiment as in experiment 36. We

have a magnetic field within which the armature is rotated. If the rotation of the armature within a magnetic field develops an electromotive force in one case, it will in every case when the same conditions are present. In the generator experiment, however, it was possible to detect the generated e.m.f. This is not so easily done in this case, hence its presence must be determined in some other way. As the armature speeds up the winding cuts the field at an increased rate. As has been shown, whenever an electromotive force is developed by the motion of a conductor, the induced pressure is always in such a direction as to oppose the motion. Accordingly, the induced pressure must be in such a direction as to oppose the applied pressure or, as it is called, it must be a counter pressure. That this must be so can be seen readily by considering what would happen if the induced pressure were in the same direction as the applied pressure. As the motor

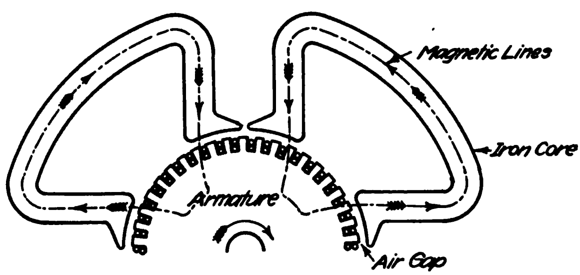

FIG. 116.

speeded up the induced pressure would be added to the applied pressure and according to Ohm's law a larger current would flow through the armature. This increase in current would increase the torque, which in turn would raise the speed. Any increase in speed would of course increase the induced pressure and so the process would go on indefinitely until the motor was destroyed. In other words, the motor would have to be loaded to prevent its running away or we may say "perpetual motion" would result. The induced pressure opposes the applied pressure and as the speed increases, the counter pressure increases reducing the current. This current is reduced to such a point that the torque is just great enough to overcome the friction at a definite speed. If the speed is decreased below this point, the counter pressure is decreased, more current flows through the armature and a greater torque results. An increase in speed increases the

counter pressure and less current is taken by the armature, and the torque is correspondingly reduced. The speed then is determined by the field strength, the applied pressure and friction, and so long as these quantities are constant the speed of the separately excited motor is constant. A practical motor running idle will behave the same way.

In this small motor the armature current is determined more by the resistance of the circuit than by the counter pressure and for this reason it does not behave exactly as a larger machine, but has some of the characteristics of a direct-current watthour meter, whose voltage coil current is determined by the resistance of the armature. If the armature had many more turns, and the field could be made much stronger, the relation of the speed to the field strength would be materially changed. When a commercial motor is operated a weakening of the field reduces the counter pressure, and more current flows through the armature. This increase in current increases the torque and the armature speeds up until the counter pressure is increased sufficiently to again control the current flow, and the torque is just sufficient to carry the load or keep the motor running at that speed. A further decrease in the field strength will be followed by a further increase in speed and a strengthening of the field will cause a decrease in the speed. Thus by strengthening and weakening the field a wide range of speed is obtained. This method of controlling the speed is quite common in practice. Although these principles cannot be fully illustrated with the small motor, that the conclusions are true can be shown by the following experiment.

183. Experiment 43. To Study the Operation of Series Motor

Apparatus.—Same as in preceding experiment.

Operation.—Connect three dry cells, motor, and ammeter in series as shown in Fig. 117. To make a series connection on the motor, connect one end of electromagnet coil to a terminal of a dry cell, and the other end of the electromagnet coil to one binding post on the brush holder. Connect the other binding post of the motor to one terminal of the ammeter, and connect the other ammeter terminal through a switch to the other free binding post on the cells. When such a connection is made the current must pass through the armature and field coils in series, and accordingly a motor so connected is called a series motor.

Close the switch and measure the current with the armature stationary. Record this value. Then start the armature while the push-button on the ammeter is kept closed. Does the current increase or decrease as the speed of the armature increases?

184. Theory.—In the series motor the current flows in series through the armature and the field. As the speed increases the counter pressure increases, which decreases the current with a resultant weakening of the field. The experiment thus shows that a decrease in the field strength is accompanied by an in-

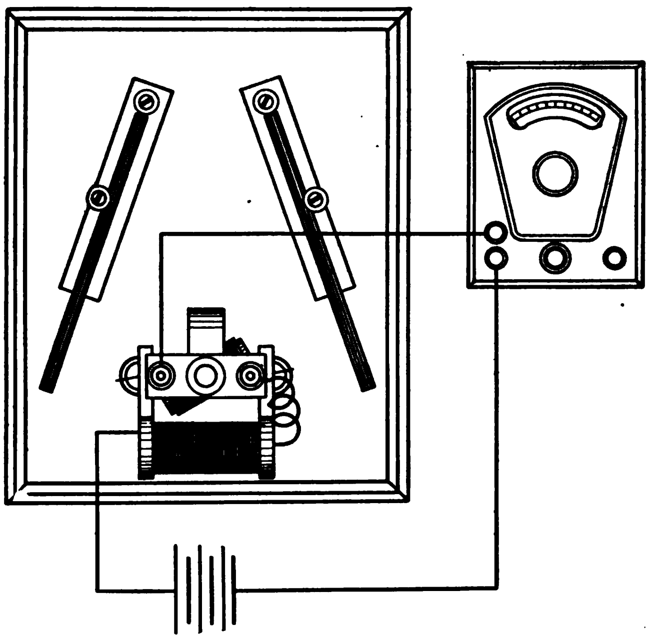

Fig. 117.

crease in the speed. Furthermore, in the series motor these two things go on together so that the speed is controlled only by the friction and the load. An unloaded series motor has the tendency to speed up and if permitted the speed may reach a high enough value to destroy the armature. This of course will not take place with the small experimental motor when only three dry cells are used. On account of the speed characteristics of the series motor it should always be direct connected to the load.

185. Experiment 44. To Study the Shunt Motor.

Apparatus.—Same as in the preceding experiment.

Operation.—Connect the terminals of the electromagnet under the lower nuts on the brush holder binding posts. Connect two dry cells in series and then connect the two free terminals to the same binding posts, and observe the operation of the motor. A motor connected in this way is called a shunt motor. Observe the direction of rotation and then exchange the battery connections. Has the direction of rotation changed? Why? Leave the battery connections as before and exchange the field connections. Have you reversed the direction of rotation? Explain. Again change the battery connections and note the direction of rotation. In what way can you change the direction of rotation of a shunt motor? The working out of the answers to the foregoing questions will be left to the student.

186. The Compound Motor.—In a compound motor the field winding consists of two parts. One part is connected in series with the armature and the other in shunt as in the preceding experiment. When the two windings are connected so that the two fields reinforce each other the winding is called *cumulative* compound. When the series field opposes the shunt field the winding is called *differential* compound.

RECAPITULATION

1. The *electric generator* is a machine for the transformation of mechanical into electrical energy.
2. The *electromotive force* of a generator is developed by rotating the conductors wound on an iron core across a magnetic field.
3. Electric generators are classified in accordance with the method of excitation. There are thus magneto, shunt, series, and compound generators.
4. A *magneto* is an electric generator whose excitation is supplied by permanent magnets.
5. A *shunt generator* is one whose field is excited by a current flowing through the field coils which are connected in parallel with the external circuit.
6. A *series geenrator* is one whose field is excited by a current flowing from the armature through field coils which are connected in series with the external field.
7. A *compound wound generator* is one which contains both a shunt and series winding.
8. With reference to excitation direct-current motors are classified in

PLATE 7.—A Westinghouse Electric Locomotive.

the same manner as generators. That is, there are series, shunt, and compound motors.

9. Compound-wound direct-current motors are of two classes, *cumulative compound*, and *differential compound.*

   (a) A *cumulative compound* motor is one in which the compound winding reinforces the shunt winding.

   (b) A *differential compound* motor is one in which the compound winding opposes the shunt winding.

CHAPTER X

WORK AND ENERGY

187. Work.—The industrial application of electricity is mainly a process of utilizing energy. That is, all industrial work from a physical viewpoint is nothing but a conversion of energy. Everyone has some idea of the meaning of the word *work*. Every farmer knows that even where the roads are alike in every respect, twice as much work is done in hauling a given load two miles as in hauling the same load one mile. The pull or force exerted by the horses is the same in the two cases, but the distance is twice as great in the first as in the second case. In hoisting a load of 2 tons to the top of a building twice as much work is done as when only 1 ton is moved through the same distance. In this illustration the distances are the same, but the loads or weights lifted are different. In general, there are two factors that enter into work—force and distance. The physical definition of work takes these into consideration. Thus, work is the result of moving a body against a force and is measured by the product of the force into the distance, in the direction of the force. Algebraically this is expressed by

$$\text{work, } W = F \times d$$

In the above definition, the phrase "in the direction of the force" must be noted carefully. For instance, moving a load of 100 lb. vertically through a distance of 100 ft. will require more work than to move the same load, or weight, the same distance along a smooth horizontal plane.

188. Unit of Work.—In the English system of units, the unit of work is the *foot-pound* and is represented by the quantity of work done in raising a pound weight 1 ft. against the force of gravity. In the metric system, the unit of work is called the *erg* and is the quantity of work done by a force of one dyne acting through a distance of 1 cm. The erg is a very small quantity and hence 10,000,000 ($=10^7$) ergs are taken as the practical unit. The practical unit is called the *joule*.

EXAMPLES

1. How many foot-pounds of work are done by a hod carrier in carrying a load of bricks weighing 40 lb. up a ladder 20 ft. high?

Solution.—

$$W = F \times d$$
$$F = 40 \text{ lb.}$$
$$d = 20 \text{ ft.}$$

And $$W = 40 \times 20 = 800 \text{ ft.-lb.}$$

2. The lifting magnet shown in Fig. 44 hoisted at one load a ton of pig iron to an elevation of 25 ft. How much work did it do?

Solution.—

$$W = F \times d$$
$$F = 2{,}000 \text{ lb.}$$
$$d = 25 \text{ ft.}$$

Hence $$W = 2{,}000 \times 25 = 50{,}000 \text{ ft-lb.}$$

3. How many ergs in 1 ft.-lb.?

Solution.—

$$1 \text{ lb.} = 445{,}000 \text{ dynes}$$
$$1 \text{ ft.} = 30.48 \text{ cm.}$$
$$1 \text{ ft.-lb.} = 1 \text{ ft.} \times 1 \text{ lb.}$$
$$= 445{,}000 \times 30.48$$
$$= 13{,}563{,}600 \text{ ergs}$$

4. How many joules in 1 ft.-lb.?

Solution.—

$$1 \text{ joule} = 10^7 \text{ ergs}$$
$$1 \text{ ft.-lb.} = 13{,}563{,}600 \text{ ergs.}$$

Hence $$1 \text{ ft.-lb.} = 13{,}563{,}600 \div 10^7$$
$$= 1.356 \text{ joules}$$

189. Energy.—Energy and work are closely related. When a weight has been lifted to a certain height, a definite amount of work has been done upon it. This work in foot-pounds is equal to the product of the height in feet by weight in pounds. The weight at the top possesses something which it does not possess at the bottom. Similarly, water at the top of Niagara Falls is capable of doing work by being run through a water wheel. When it leaves the water wheel and enters the river at the bottom of the falls, it is no longer capable of doing work. That is, it has parted with its ability to do work in descending from the top to the bottom of the falls. The *energy* of a body or a system of bodies is its capacity for doing work. It is measured by the work which can be performed. Energy is classified under two

heads *potential* and *kinetic*. The energy that a body possesses by virtue of its position is called *potential*. Thus, the water at the top of the falls is capable of doing work on descending to a lower level. It thus possesses energy of position. Similarly, a weight lifted to a given height possesses energy of position. If the weight be dropped, the elevation will decrease, but its energy will not decrease until it strikes the earth and transfers its energy to some other body. When only a short distance, say 1 ft., from the lowest point in its fall, its energy of position is very small, and just before it strikes, the energy of position is practically zero. The velocity of the body is maximum or greatest at the time of striking, and zero at its highest point. The body possesses energy by virtue of its velocity. This energy due to the velocity of the body is called *kinetic*. The simple pendulum will help make this clear. The simple pendulum at the extreme position of its swing possesses energy due to its elevation. When released, this elevation decreases until the pendulum reaches the lowest point of its swing when its elevation is zero, but its velocity is a maximum. The potential energy has all been changed to kinetic. As the pendulum passes beyond the middle point of its swing, the velocity decreases, hence the kinetic energy decreases. The elevation of the pendulum increases, and, therefore, the potential energy increases. This change continues until the pendulum reaches the other extremity of its swing, when the energy is again wholly potential. The sum total of the energy of the pendulum is constant at any point of the swing. That is, the sum of its kinetic and potential energy is a constant quantity.

As already stated, the unit of energy is the same as the unit of work, and the energy of a body is equal to the amount of work expended upon the body. This is a simple statement of the fundamental principles of dynamics, viz., the *Principle of the Conservation of Energy*. Newton limited his laws to motion, in reality they may be considered as applying to energy as well. Thus, the statement "action is equal to reaction" is also true with reference to the expenditure of energy. No body is capable of doing work unless work is first done upon it. All machines act simply as means of transferring energy from one system to another system. The full appreciation of this principle is of comparatively recent date. Perhaps the most important discovery in the realm of mechanics is the following: The sum of the kinetic and potential energies of a body or system of bodies

is a constant quantity, unless it be changed by some external influence. In other words, the energy of a system cannot be created or annihilated. No human being can create or destroy energy. A distinction must, however, be made between the total amount of energy of a body or system of bodies, and the amount of energy that the system is capable of transferring to another system. In all mechanical operations some energy is dissipated or wasted or becomes unavailable. For instance, a simple pendulum released at the extreme position of its swing, will not of itself reach the same point on its return. This is due to the fact that some of its energy has been transferred to the air, and another portion has been dissipated on account of the friction and stiffness of the string supporting it. This law of the conservation of energy is fundamental in all energy transformations.

190. Power.—In everyday usage, the word power has many different meanings. It is often confused with work. *Power* is not work, but the time rate of doing work. As an illustration suppose that one man carries 2,000 bricks to the second story of a building in one day while it takes another man two days to do the same work. Evidently, the total amount of work done in the two cases is the same although the rate at which the work is done is different. The second man's rate of doing the work is only one-half that of the first man's rate. Technically this is explained by saying that the power of the two men is different. The power of the first man is double that of the second man. Power is then the amount of work done in some unit of time. In engineering practice the unit of time is usually the minute or second. In algebraic symbols power is expressed by

$$\text{Power, } P = \frac{\text{Work}}{\text{Time}} = \frac{w}{t}$$

$$= \frac{F \times d}{t}$$

$$\text{or } P \times t = F \times d = \text{ work}$$

191. Units of Power.—In the English system of units the unit of power is the rate of doing 33,000 ft.-lb. of work in one minute. This unit is called the *horse-power*. In the metric system of units which is used in electrical work the unit of power is the *watt*. The *watt* is defined as the rate of doing one joule per second.

It is very important that the distinction between *power* and *work* be clearly understood.

EXAMPLES

1. Niagara falls are about 160 ft. high. It is estimated that 700,000 tons of water pass over them every minute. If all of the energy of this water could be utilized, what horse-power could be developed?

Solution.—

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

The work or energy of the 700,000 tons of water is $700,000 \times 2,000 \times 160$ ft.-lb. 1 h.p. = 33,000 ft.-lb. per minute.

Hence,
$$\text{Power} = \frac{700000 \times 2000 \times 160}{33000}$$
$$= 6,787,878 \text{ h.p.}$$

2. How many watts in 1 h.p.?
In the solution of example 4, page 194, it was shown that 1 ft.-lb was equal to 1.356 joules. One horse-power is equal to 550 ft.-lb. per second; hence 1 h.p. must equal $550 \times 1.356 = 746$ joules per second. Since one watt equals one joule per second, then 1 h.p. equals 746 watts.
3. How many kilowatts of power could be developed from Niagara falls if all of the energy were utilized.
Solution.—Since 1 h.p. equals 746 watts the total watts developed would be

$$6,787,878 \times 746 \text{ watts}$$

But one kilowatt = 1,000 watts,
Hence kilowatts developed is

$$\text{Kw.} = \frac{6787878 \times 746}{1000}$$
$$= 4,953,657 \text{ kw.}$$

192. Electricity and Electrical Energy.—It is impossible at present to explain electricity in terms of anything simpler. We know electricity only through its manifestations or effects. It matters not, so far as practical results are concerned, whether electricity is a form of energy or only a vehicle of energy. The fact is that energy is always manifest in connection with the electrical current, and that this energy can be transformed into other forms of energy. It may also be transferred from point to point along a conductor without the necessity of mass motion. It is this ability to transfer energy without the motion of masses of matter that makes electricity the most successful medium for

transferring energy over long distances. The transformation of electrical energy is electrical work and is accomplished in many ways. The rate of transformation is power just as in the case of other forms of energy.

193. Electrical Work.—The derivation of the principles of electrical work or energy will undoubtedly be better understood if analogies are used. The quantity of water flowing through any pipe in a given time may be expressed as the strength of current multiplied by the time. A unit current of water has no name. If a unit current gives a cubic foot (62.3 lb.) of water in one second, a two-unit current will give 2 cu. ft. of water per second or 10 cu. ft. in 5 seconds.

Similarly, a unit current of electricity flowing for 1 second gives a definite quantity of electricity. This quantity is called the *coulomb*. The total quantity conveyed by a constant current of I amperes in t seconds is then given by $Q=It$. Again referring to the analogy of water flowing through pipes one may consider unit work to be done when 1 cu. ft. of water is delivered under a head of 1 ft. The amount of work done by a head of h feet, delivering q cubic feet of water will be hq. But electrical pressure is analogous to water pressure, or head, and the quantity of water is analogous to the quantity of electricity or coulombs. A current delivering Q coulombs of electricity under a pressure of E volts will then do EQ units of work. This may be expressed algebraically, thus:

$$\begin{aligned}\text{work } &= E \text{ (volts)} \times Q \text{ (coulombs)}\\ &= EQ \text{ joules}\end{aligned}$$

The values of volts, coulombs, and joules have been so selected that the product of one volt by one coulomb gives one joule. It has been shown, however, that Q, the quantity, is equal to It, the current by the time. We may then write the expression for work thus:

$$\text{Work, } w, = EIt.$$

When E is in volts, I in amperes and t in seconds the result is in joules. If t is 1 second, we have

$$w = EI \text{ joules, per second.}$$

One joule per second is 1 watt, hence in general, volts $\times$ amperes gives watts. In electrical work the joule is a small

unit of energy so 1,000 watts for 1 hour is usually used. This unit is called the kilowatt-hour. It is equal to 3,600,000 joules.

EXAMPLES

1. What power is being developed by a direct-current generator when it gives out 75 amperes under a pressure of 220 volts?

Solution.—

Power in watts = volts × amperes

$= I \times E$

$I = 75$ amperes

$E = 220$ volts

Hence $P = 75 \times 220 = 16{,}500$ watts

1,000 watts $= 1$ kw.

Then $P = 16{,}500 \div 1{,}000 = 16.5$ kw.

2. A house is lighted with 100 lamps each taking 0.55 ampere at 110 volts. How many watts are necessary to operate the lamps?

Solution.—Since each lamp takes 0.55 amperes, and incandescent lamps are usually connected in parallel, then the total current is $0.55 \times 100 = 55$ amperes.

$$\text{Watts} = 55 \times 110$$
$$\text{Watts} = 6{,}050$$

3. The armature current of a 400-volt direct-current motor is 30 amperes at a certain load. Neglecting armature losses, how much electrical power is converted into work?

Solution.—

$$\begin{aligned}\text{Power} &= I \times E\\ &= 30 \times 400\\ &= 12{,}000 \text{ watts}\\ &= 12 \text{ kw.}\end{aligned}$$

4. What is the horse-power developed by the motor in example 3?

Solution.—

$$1 \text{ kw.} = \frac{1000}{746} \text{ h.p.}$$

Hence $$12 \text{ kw.} = \frac{12 \times 1000}{746} = 16.1 \text{ h.p.}$$

194. Power Drop.—According to Ohm's law the pressure drop across a resistance R, when a current of I amperes is flowing, is $I \times R$ or

$$E = I \times R$$

If E is the pressure which sends a current of I amperes through the resistance, then the power spent in the wire is IE watts. Multiplying both sides of $E=IR$ by I we get

$$EI=I^2R$$

Since IE is the power spent in the resistance, and $IE=I^2R$, then the power loss is equal to I^2R watts. That is, the power spent in forcing a current through a resistance is equal to the square of the current multiplied by the resistance.

EXAMPLE

1. The resistance of an electric flatiron is 25 ohms. What is the power spent in the iron when it takes 4.5 amperes?

Solution.—

$$\begin{aligned} \text{Power } &= I^2R \\ I &= 4.5 \\ R &= 25 \\ \text{Then } P &= 4.5\times 4.5\times 25 \\ &= 506.25 \text{ watts} \end{aligned}$$

2. If the electrical energy costs 12 cents a kilowatt-hour, how much will it cost to operate the iron for 3 hours?

Solution.—

1 kw.-hr. = 1,000 watts for 1 hour
506.25 watts = 0.506 kw.
$0.506\times 3=1.518$ kw.-hr. used.
$1.518\times 0.12=18.2$ cents, cost of operating the flatiron for 3 hours.

3. A projection lantern is operated on a 110-volt circuit. The resistance of the controlling rheostat is 3.5 ohms. If the voltage drop across the lamp is 50 volts what current does the lamp take and how much power is wasted in the rheostat?

Solution.—The voltage drop across the rheostat, which must be the difference between the drop across the lamp and supply voltage, is $110-50=60$ volts. By Ohm's law,

$$\begin{aligned} I &= \frac{E}{R} \\ E &= 60 \\ R &= 3.5 \\ \text{Then } I &= \frac{60}{3.5}=17.1 \text{ amperes} \\ \text{The power loss is } I^2R &= 17.1\times 17.1\times 3.5 \\ &= 1{,}028 \text{ watts, nearly} \end{aligned}$$

195. Heating Value of the Electric Current.—The student has observed the heating effect of the electrical current in con-

nection with several of the experiments. The relation between the quantity of the electrical energy and the quantity of heat has not been explained. The power loss in a conductor is given by I^2R. This is all converted into heat and the exact relation was first determined by James Prescott Joule, an English physicist. He did this by immersing a conductor of known resistance into a known weight of water and measuring the current, time and temperature. The results of his experiments show that *the heat generated in a conductor is proportional to the time, to the resistance, and to the square of the current.* This condition may be written in algebraic form as follows:

$$\text{Heat} = KI^2Rt$$

This is evidently the energy loss in a conductor multiplied by a conversion factor K. This factor is introduced on account of the fact that the unit for the measurement of heat is not the same as that for the measurement of electrical energy. The unit for heat measurement is the quantity of heat required to raise the temperature of 1 grm. of water from 15 to 16 degrees cent., and is called a *calorie*. The calorie is equal to 4.181 joules. That is, the heat unit is 4.181 times the electrical unit. To convert joules to calories we must multiply the joules by $\frac{1}{4.181} =$ 0.24. This 0.24 is the constant K which we can replace and get

$$\text{Heat, in calories, } = 0.24I^2Rt$$

where I is in amperes, R in ohms, and t in seconds.

The mechanical engineering unit of heat is called the *British thermal unit,* which is abbreviated to B.t.u. A B.t.u. is the heat required to change the temperature of 1 lb. of water 1 degree Fahrenheit. One B.t.u. $=252$ calories.

EXAMPLES

1. How many calories of heat are developed in a flatiron per hour if the iron takes 5 amperes at 120 volts?

Solution.—

$$\text{Heat} = 0.24I^2Rt$$
$$I = 5 \text{ amperes}$$
$$R = 24 \text{ ohms}$$
$$t = 3{,}600 \text{ seconds}$$

Then $H = 0.24 \times 5 \times 5 \times 24 \times 3{,}600$

$= 518{,}400$ calories

It is perhaps a little simpler if we remember that $I^2Rt = EIt$. For

$$5 \times 120 \times 3{,}600 = 5 \times 5 \times 24 \times 3{,}600$$

It is not necessary to find the resistance first.

2. A 62-in. Cutler-Hammer lifting magnet takes 55 amperes at 220 volts. This is all converted into heat after the magnetic field is built up. How many calories of heat are developed in the winding in 5 minutes?

Solution.—

$$\text{Heat} = 0.24\ EIt$$
$$E = 220 \text{ volts}$$
$$I = 55 \text{ amperes}$$
$$t = 300 \text{ seconds}$$

Then
$$H = 0.24 \times 220 \times 55 \times 300$$
$$= 871{,}200 \text{ calories}$$

This amount of heat will raise the temperature of 100 lb. of iron about 170 degrees cent. in the same time. This fact shows the necessity of designing the magnet so that the heat produced in the coil may be conducted to the outside quickly and easily and radiated into space.

196. Some Practical Applications of the Heating of Electric Currents.—Undoubtedly the most common application of the heating of an electric current is the incandescent lamp. The conductor in one type of incandescent lamp consists of a carbon filament enclosed in a glass globe from which all air has been exhausted. The light is produced by the current heating the

FIG. 118.

FIG. 119.

filament to a bright yellow. A 16-candle-power lamp designed for a 110-volt circuit has a resistance of about 200 ohms when hot and takes a current of about 0.55 ampere. It is called a 60-watt lamp.

Within recent years metallic filament lamps have to a great extent displaced the carbon lamps. The best lamps of this type

have a filament of an alloy of tungsten and osmium. The metal tungsten has a high melting-point and may be heated to a higher temperature than carbon before it disintegrates. This property makes the lamp more efficient by converting a greater percentage of the electrical energy into light. The present tungsten lamps use about 1.25 watts per candle-power. The General Electric Company is making preliminary announcements of new lamps whose efficiency is much better. The lamp will, perhaps, be on the market by the time this text is off the press. A carbon and a tungsten lamp are shown in Figs. 118 and 119.

FIG. 120.

The use of electrical energy for the production of high temperatures has resulted in the production of materials, such as carborundum, tungsten, commercial graphite, emery, calcium carbide, aluminum, etc. The electric furnace has created an entirely new industry; before the application of high tempera-

FIG. 121.

tures was possible, the above-named materials could not be produced at reasonable cost or in commercal quantities.

Other common practical applications of the heating effect of electric currents are the many forms of arc lamps. The old style of carbon arc lamp is also being displaced by new forms. One form called the flaming arc lamp is shown in Fig. 120.

Wherever electric energy is comparatively cheap the heating effect of the electrical current may be used to operate many heating and cooking devices that are now on the market. Some forms of these are shown in Fig. 121.

197. Cost of Electric Heating.—The transformation of electrical energy into heat by means of a resistance takes place at an efficiency of 100 per cent. Nevertheless, whether it is cheaper to heat or cook with electricity than with some other transformation of energy into heat will depend upon the relative cost of electrical and other forms of energy. For the purpose of enabling a comparison to be made, Mr. H. O. Swoboda, in the *Electric Journal* for July, 1913, published the following:

COMPARATIVE COST OF HEAT GENERATED BY COAL GAS AND ELECTRICITY

Coal develops at an average a heat of 12,000 B.t.u. per pound. The efficiency of coal-burning heating apparatus averages about 10 per cent. Effective heat obtained from 1 lb. of coal =1,200 B.t.u.; from 1 short ton of coal =2,400,000 B.t.u.

Gas develops at an average a heat of 660 B.t.u. per cubic foot. The efficiency of gas-burning heating apparatus averages about 20 per cent. Effective heat obtained from 1 cu. ft. of gas =132 B.t.u.; from 1,000 cu. ft. gas =132,000 B.t.u.

Electricity develops a heat of 3,413 B.t.u. per kw.-hr. The efficiency of electrically heated apparatus averages about 80 per cent. Effective heat obtained from 1 kw.-hr. =2,730 B.t.u.

Based on these figures, the same amount of useful or effective heat is generated by

1 kw.-hr. or 20 cu. ft. of gas or 2.25 lb. of coal.

A table of comparison showing prices at which electricity would have to be sold, to compete with coal and gas, if there were no other advantage in using electrically generated heat, is given on next page.

At the present prices for electrical energy the cost of heating by electricity, with few exceptions, is higher than by coal or gas and other reasons for its use must exist. Although many reasons can be enumerated why electrical energy may be used for household heating, the advantages of electrical heating may be summed up under one heading, convenience.

TABLE IX

Coal per ton	Electricity per kilowatt-hour	Gas per 1,000 cu. ft.	Electricity per kilowatt-hour
$1.50	0.17 cent	$0.10	0.2 cent
2.00	0.23 cent	0.20	0.4 cent
2.50	0.28 cent	0.30	0.6 cent
3.00	0.34 cent	0.40	0.8 cent
3.50	0.39 cent	0.50	1.0 cent
4.00	0.45 cent	0.60	1.2 cents
4.50	0.51 cent	0.70	1.4 cents
5.00	0.57 cent	0.80	1.6 cents
5.50	0.62 cent	0.90	1.8 cents
6.00	0.68 cent	1.00	2.0 cents
		1.25	2.5 cents
		1.50	3.1 cents
		1.75	3.6 cents

RECAPITULATION

1. *Work* is defined as the product of a force and the displacement produced by or against this force in the direction of the force.
   (a) The unit of work in the English system of units is called a *foot-pound.* The *foot-pound* is the work done in lifting a weight of 1 lb. 1 ft. high against gravity.
   (b) In metric units the unit of work is the *joule.* A *joule* is equal to 10,000,000 ergs. An *erg* is the work done by a force of one dyne acting through a distance of 1 cm.
2. *Energy* is the ability of doing work. The units for measuring energy are the same as those for work.
3. *Power* is the time rate of doing work.
   (a) The English unit of power is the *horse-power.* A *horse-power* is the rate of doing 550 ft.-lb. of work per second.
   (b) The metric unit of power is the *watt.* A *watt* is the rate of doing 1 joule per second. One horse-power = 746 watts.
   A *kilowatt* = 1,000 watts.
4. Work in direct-current circuits is obtained by multiplying volts by amperes by time. Algebraically it is given by

$$\text{Work} = EIt$$

   The commercial unit for electrical energy or work is the *kilowatt-hour.* A *kilowatt-hour* is the work done by 1 kw. in 1 hour; it equals 3,600,000 joules.
5. Power in direct-current circuits is obtained by multiplying volts by amperes, or

$$\text{Power} = EI \text{ watts}$$

6. *Power drop* or *loss* is the loss per second when a current of I amperes flows through a resistance R. It is equal to I^2R watts.
7. A *calorie* is the quantity of heat required to raise the temperature of 1 grm. of water from 15 to 16 degrees cent. One calorie = 4.181 joules.

   A *British thermal unit* is the quantity of heat required to change the temperature of 1 lb. of water 1 degree Fahrenheit. One B.t.u. =252 calories.

   The *heat generated* by a current of I amperes in a resistance of R ohms in time t seconds is given by

$$\begin{aligned} \text{Heat (calories)} &= 0.24\, I^2Rt. \text{ calories} \\ &= 0.24 \text{ watts} \times t \\ \text{Heat (B.t.u.)} &= 0.00095\, I^2Rt \\ &= 0.00095 \text{ watts} \times t \end{aligned}$$

INDEX